MODERN GEAR PRODUCTION.

Paper presented to the Institution, Manchester Section by C. Eatough.

IN this paper I have been asked to give you some information about the underlying principles involved in gear cutting machines, rather than detailed descriptions of the machines themselves. To a great extent the requirements of the automobile industry are responsible for the fact that nearly all the modern high production gear cutting machines have been developed to deal with the various gears required for motor vehicle work. I think that certain highly specialised machines used principally in the motor trade are not of direct interest to the majority of production engineers in this district, and for this reason I propose to confine myself to the machines such as are met with in the average engineering shop dealing with work of a general nature. To many of you the greater part of what I have to say will be familiar, but dealing as I do with gearing users in all classes of business I find the underlying principles of gear production are frequently misunderstood, with the result that machines are not always run to their best advantage, neither are the gears always designed with due consideration being given to the limitations covering their production.

Shape of Teeth.

The involute to a circle is used almost without exception as the curve for the profile of gear teeth to-day. There are an infinite number of curves which might be used instead, but the involute happens to possess many advantages which make it admirably suited to accurate production. I shall not attempt to prove that the involute is capable of transmitting uniform velocity from one tooth to another, as you are no doubt quite familiar with this property of the curve. I will briefly state that involute teeth are capable of transmitting uniform velocity from one shaft to another and under certain conditions a series of gears with involute teeth will all mesh with one another, and in each case still give the required uniform velocity of transmission. Involute gears can also be run at centre distances which do not correspond to their so-called standard pitch diameters and still transmit uniform velocity.

All contact takes place on line of action. It has often been said that the straight line is the simplest shape which can be produced to a high degree of accuracy. This is the foundation of modern

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gearing. The involute to a circle of infinite radius is a straight line, so we now have an involute which can be produced accurately, quickly, and cheaply. I have mentioned that under certain conditions a series of involute gears will all mesh correctly with one another. By taking advantage of this property it is possible to generate series of involutes from the involute straight line. This is the basic principle of gear generating machines.

I have said that all contact takes place along a straight line called the line of action. In some machines, such as the Maag or Sunderland machine, the straight line involute is used directly as the actual cutting tool. In others, such as the Fellows machine, one has to go beyond the machine itself to find the straight line, in this case to the machine used for producing the pinion type cutters. The cutters are generated from a straight line in the form of a straight trimmed grinding wheel, and in turn are used to generate gears on the actual gear cutting machine.

Machines arranged to cut gears with the aid of formed cutters, or with the use of tools restrained to move in certain predetermined paths under the control of formers, are still used to a small extent, one notable modern machine of this type being the Orcutt gear grinder, in which the shape of the grinding wheel is obtained by trimming the wheel by diamonds operated by a pantograph mechanism embodying former plates which are large scale reproductions of the required tooth profile.

Generation.

A few words on generation will not be out of place since this has such an important bearing on gear production. The majority of machine tools in everyday use depend on generation, of one kind or another, for their operation. All machining operations whereby the cutting tool and the work in progress are restrained to move in certain paths can be classed as generation. In this manner a lathe engaged on turning a shaft is generating a cylinder by means of a combination of the rotary motion of the shaft with a linear movement of the cutting tool along a line parallel to the axis of rotation of the shaft. Similarly, a planing machine generates a plane surface by the combination of the "to and fro" motion of the work and the cross traverse of the cutting tool. In the examples mentioned, the cylinder or plane is formed by a large number of successive cuts, each cut having the profile of the cutting tool. In other words, the generation is intermittent. Actually, the required shape is formed as an envelope of a series of curves, each of the shape of the nose of the cutting tool, and spaced apart by an amount equal to the feed of the cutting tool per cycle.

The fact of the generation being intermittent is of considerable importance as this influences the degree of finish which is obtained.

The elimination of the effects of intermittent generation is relatively easy in some cases, as, for example, a planer tool may be given a broad edge greater than the traverse per stroke, so that the overlapping cut does away with the grooves resulting from the use of a round nose tool. This is the combination of a forming and a generating operation.

Unfortunately, in gearing generation it is not always possible to eliminate the intermittent generation, and this presents serious problems with certain types of machines. This has a bearing on the choice of the most suitable machine for certain gears. With the lathe and planing machine previously mentioned, the degree of finish depends not only on the shape of the cutting tool but also on the feed. A good finish can be obtained even with a relatively pointed tool, if the feed per cycle is kept sufficiently fine. With some types of gear cutting machines the same applies; the feed per cycle or "unit of generation," if I may use such a term, being under the control of the operator. In one type of machine in common use this does not apply; the feed having no connection at all with the generation motion. I refer to the spur gear hobbing machine in which the unit of generation depends on the number of teeth in the gear being cut and on the number of threads and gashes in the hob.

If we consider a pair of involute gears in mesh, they will make contact with one another on the involute portions of the teeth only. Broadly speaking, contact between a pair of teeth commences between the top of one tooth and the bottom of the involute of the mating tooth. As the gears roll with one another, the point of contact moves down one tooth and up the other by a combination of sliding and rolling, until the teeth pass out of contact. An important condition is that the continuity of motion must be preserved by another pair of teeth coming into action before the previous pair separate. Within certain limitations, which do not concern us at present, the involutes follow absolutely the profiles of the mating teeth. This only occurs during the transmission of uniform velocity. By inverting the process and applying uniform velocity to one of the involutes, and also to a blank representing the gear to be cut, we have the essentials of a gear generator.

The driven involute will describe another involute on the blank, which is the correct shape for a tooth which in turn will transmit uniform velocity. The Fellows machine, in effect, comprises a pair of spur gears rolling together in the manner described. During the rolling motion the cutter which is an involute gear, has applied to it an axial motion which does the cutting and so enables the involute shaped teeth to be generated on a blank having thickness. The cutter and blank are geared together in the required ratio to cut a

certain number of teeth in the blank when using a cutter which has a number of teeth depending on its size and pitch. Means are provided for relieving the cutter during the idle return stroke to prevent rubbing on the gear under operation. The generating motion is continuous; the cutter and blank rotate in unison until all the teeth are formed.

If the pinion type cutter is replaced by a cutter having an infinite radius we have the rack cutter. The gear generating machines using rack cutter, operate on the same principle as the Fellows machine, but the generating motion cannot be continuous, since the length of the rack cutter must as a rule be considerably shorter than the circumference of the gear being cut.

The method adopted to overcome the difficulty is to arrange for the generating motion to continue for the space of one pitch only, after which the cutter is withdrawn from the work. When the cutter is clear of the blank, the cutter is caused to move a distance equal to one pitch along the cutter pitch line, and it is then brought back into contact with the work. By repeating the cycle and retracting the rack cutter one pitch at the end of each forward travel of one pitch distance, the entire circumference of the gear is eventually covered.

Both systems have obvious limitations. A rack cannot mesh with an internal gear under any conditions, and such gears must be generated by machines employing pinion type cutters.

For large pitch external gears, pinion type cutters become very cumbersome and expensive so that the rack cutter shows to great advantage. In fact, for very large pitch gears a single rack tooth is employed as a cutter.

With the pinion and the rack cutter machines, the degree of finish obtained on the gear being cut depends on the number of cutting strokes per tooth. This is controlled by the operator and is to a great extent independent of the generating motion.

Hobbing Machines.

The hobbing machine is perhaps the best known method of cutting gears. In the hobbing of spur gears, advantage is taken of the fact that a worm will mesh with a spur gear having a pitch and pressure angle equal to the worm pitch and pressure angle on the normal section to the thread.

An oblique section of a cylinder is an ellipse. If we take an oblique section of a worm lying at right angles to the thread, we have an ellipse which at the point of normal section has teeth disposed along it. If the worm thread is so shaped that the normal section of the thread is the same shape as the teeth of a spur gear having the same radius of curvature as the ellipse at the point of the normal section, then another method of cutting spur gears presents

itself. For all practical purposes the worm meshes with a spur gear in a similar way to the meshing of a spur gear having the same radius of curvature as that of the normal worm section. If the worm and spur gears are rotated together in the ratio of the number of threads in the worm to the number of teeth in the wheel the two sets of teeth will follow the profiles of one another exactly as a pair of meshing spur gears. It will be necessary to tilt the worm axis so as to bring the normal section on a plane at right angles to the axis of the gear. If during the rotation of the worm in mesh with the wheel a traverse is imparted to it along a line parallel to the axis of the wheel, then as the worm passes across the face of the gear all portions of the wheel teeth will be contacted by the threads of the worm.

It only remains now to provide the worm threads with cutting teeth and we have the familiar hobbing machine. A spur gear hob is often considered as a rack cutter, but actually this is not the case as the normal section is elliptical and not straight. The point is not of much importance in the hobs commonly used for cutting spur gears, as these tools are as a rule provided with one start thread and have a low lead angle. With multi start hobs, however, the curvature of the normal section must be given consideration. In the case of single start hobs the radius of curvature of the ellipse at the point of section is large and the shape of the teeth approximates to those of a rack. The ellipse in the multi start hob has a smaller radius of curvature and the profiles of the hob teeth must be shaped to correspond to the shape of the teeth of a gear of the same radius. We now come to a very important point in connection with the generating principle of hobs. With the pinion cutter and with the rack cutter, the number of strokes of the cutting tool during the generation of one tooth of the gear is under the control of the operator but with the hob this is not the case.

Consider a single start hob engaged in cutting a spur gear. The hob will make one revolution during the passage of each tooth of the gear being cut. If we assume that the hob has eight flutes or gashes, then each gear tooth will have been acted upon by eight cutting-edges. One of these cutting edges will come into action every eighth of a revolution of the hob. The rotation of the gear and hob in unison is quite continuous. The hob is only engaged in finishing part of a gear tooth eight times during a revolution, and during the intervals between the operation of one of the hob teeth and the next the rotation of the gear blank is still in progress. This results in the gear teeth being formed as a series of facets each of which is tangential to the required involute curve. The rate of down feed of the hob does not have any effect on the size and number of facets; these being determined by the number of teeth in the gear, and the number of gashes in the hob, and also on the number of

starts in the hob. The effect of the facets is to leave metal which should have been removed, so that the greater the number of facets the nearer we approach to the theoretical involute. The number of facets formed in any particular case depends on the angular movement of the gear blank per revolution of the hob. With gears having small numbers of teeth, the angular movement per revolution of the hob is great and large flats result on the tooth profiles being generated and the same is the case with multi-start hobs. If single start hobs are used to generate gears with large numbers of teeth, the facets are so large in number and small in size as to be difficult to see.

Worm Hobbing Machines.

In cutting worm wheels a hob which is a replica of the worm is fed radially into the wheel blank, and so generates the teeth. As was mentioned, the teeth are formed as a series of facets. With worm gears, however, the conditions may be very favourable for the formation of exceedingly large facets and special means are used to overcome the trouble. From considerations of design of the finished gears it is frequently necessary to have large pitch hobs small in diameter and so having few teeth. Usually the hobs are of multi start, and are used to cut gears having small numbers of teeth. Such a hob if fed straight into the blank in a radial direction would form large facets on the teeth, to the detriment of quiet running. During the rotation of the hob and blank in the usual manner of a hobbing machine another motion is introduced. The hob is slowly traversed in a direction along its axis, and an additional rotary movement is imparted to the wheel blank so as to keep it in correct pitch with the sliding hob. This has the effect of generating the facets slightly out of phase with one another during each revolution of the gear blank. In this manner the facets are reduced in size. By making the axial feed of the hob sufficiently fine the facets can be made imperceptible.

When worm wheels have to be cut which do not justify the expense of making costly hobs, advantage is taken of the method just described to cut the gears with a hob having one tooth only ; this is the flytool, used where the cost of a suitable hob would be prohibitive. Without the axial traverse a flytool would cut each tooth profile as one large facet, but with the traverse the facets are slightly out of phase each revolution of the blank, and well formed teeth result. Take the case of a worm wheel generator using a flytool. The tool is mounted in a mandrel carried on a slide which traverses slowly across during the cutting operation. The screw operating the slide is interconnected by the change gears shown to the mechanism which adds to or subtracts from the rotary motion of the

blank in order to keep it in pitch with the flytool as it traverses tangentially across the face of the gear.

Worm gears show to advantage for small reductions, and this necessitates the cutting of gears having small numbers of teeth and multiple starts.

Many worm gear generators are constructed to cut gears with a minimum ratio of about three to one. One such machine has been converted to cut gears of ratio one to one, by the addition of an auxiliary work table mounted on the standard table. The table drive ratio has been reduced by about three to one with the result that the table rotates about three times as fast as the standard table when using the same ratio of change gears. When the auxiliary table is in use the main table is locked. Although the converted machine operates quite successfully, it is not suited for high production.

The application of heavy flywheels to gear cutting machines deserves much more attention than has so far been given to this cheap and simple method of ensuring uniform running of members subjected to intermittent loads. The intermittent loads may be due to the cutter itself, or may be due to inaccuracies of the various members of the machine. Such inaccuracies in a modern machine of good design may be very small indeed, but the high degree of accuracy necessary to-day in obtaining quiet gears does not permit of any device which helps their elimination being neglected. Whatever inaccuracies may be present are damped out before being transmitted to either the cutting tool or the work table. The work table on this machine is driven by a pair of double helical gears and any backlash between these gears is taken out by adjusting the pinion in an axial direction. In this manner the gears operate as a pair of single helical gears of half the face width of the double helicals.

Single and Double Helical Gears.

These, as is the case of spur gears, may be provided by either rack cutters or pinion cutters. The cutters may either be arranged along a line at right angles to the tooth being cut or may be perpendicular to the gear axis in which case the required angle is obtained on the cutter itself. In the Sunderland machines the cutter head slice is vertical and on the completion of each cycle, the cutter is withdrawn when indexing takes place, after which the cutter is again fed to depth. With the Maag machine the generating roll takes place on the work saddle, whilst with the Sunderland machine the generation takes place on the cutter head, the gear rotating so as to keep in pitch.

Where a Fellows' machine employs a helical cutter, the cutter oscillates up and down under the control of helical guides carried in the head of the machine. A different cutter is required for each

hand of gear being cut, and the angle obtained cannot be altered without changing the cutter and guides. Four standard guides are available. Straight for spur gears, and helical guides for giving angles of approximately 15°, 23°, and 45°.

Internal helical gears may be cut with the same facility as external gears. Double helical gears with the Fellows' system are cut as two single helical gears of different hands, each cutter running into a gap in the centre of the blank. With the Sunderland system the machine uses two cutters; no gap is required, as each cutter removes the chip left by the other where it reaches solid metal in the centre of the gear.

Worms and Screws

Worms and screws are usually produced by milling operations, the work being traversed past a suitably shaped milling cutter at a pre-determined rate. The shape of the milling cutter profile is exceedingly difficult to determine theoretically and in consequence in worm gear design the ideal tooth profile may frequently have to be modified slightly to suit the method of manufacture. A worm thread is a helix and unfortunately, a milling cutter producing a helical thread will not cut a space of the same profile as itself, due to the interference which occurs. The amount of interference depends on several factors including the helical angle of the thread, the depth of cut, the diameter of the cutter and of the worm, and on the profile of the cutter form. Some of these factors are under control to a certain extent, but others are not. The result is that within limits, whatever worm shape is obtained may have to be taken as the basis, and the corresponding worm wheels cut to suit it. All important worms have their profiles ground after their threads are hardened and the same conditions apply during the grinding operation as during the initial milling. The hob used for cutting the worm wheels must have the same profile as the worm threads, so here we have another limitation to the choice of thread profile. It must be such that it is possible not only to grind the worm threads, but also to make and relieve a hob having the same profile.

In the case of a worm milling machine suitable for rapid production on worms of comparatively large pitch, I would like to call your attention to the provision for ensuring a satisfactory drive to the cutter. In the first place the cutter is provided with staggered teeth so as to smooth out as far as possible the intermittent heavy shock as each tooth comes into action. The cutter profile is unsymmetrical, so that the cutter mandrel slopes away from the worm under operation. By this means a large diameter gear provided with heavy rigid bearings may be used for driving the cutter without

interfering with the work. The cutter spindle has mounted in it a heavy flywheel which improves the smooth running of the cutter, By isolating the cutter and cutter drive mechanism from heavy shocks in this manner, much improved production and longer cutter life results.

The grinding of worm threads after hardening may be done with a double conical wheel similar in shape to the worm milling cutter. The machines are usually arranged to index from one start to another after each pass of the grinding wheel. In this manner the threads are gradually brought down to size. It is usual to operate on one side of the threads at once.

A comparatively recent development in worm grinding is a machine in which an annualar wheel is utilised, the grinding taking place on the periphery. In this manner very little interference occurs and it is a comparatively easy matter to trim the wheel to any required profile. The wear of the wheel is fully compensated by feeding the wheel forward as it wears against trimming diamonds which maintain a fixed position relative to the worm. It is claimed also that this system of grinding gives enhanced production and a higher degree of finish, in view of the wheel operating more in the nature of a cylindrical grinding operation as compared with the double conical wheel which operates on the face.

Bevel Gears.

Take a pair of bevel gears in engagement. Considering the back cones of the gears we have a pair of spur gears whose numbers of teeth are such as to correspond in shape to the tooth of the bevels. In generating the bevels it is these equivalent gears which we must consider. In the bevel machine the basic straight line of the system is the tooth of a crown gear which corresponds to the rack of a spur gear system. The bevel teeth may be generated in exactly the same way as a spur gear with a rack shaped cutter, but difficulty ensues due to the fact that the pitch of the bevel tooth is gradually diminished as the apex point is approached. Although a rack shaped tool of certain size may be suitable for cutting the teeth of the large end of the gear such a tool would be much too thick for cutting the teeth of the small end of the gear. This being so we require some means by which one tool can cut both the large and the small ends of the teeth of the gear. The method most commonly in use is to employ two tools, the cutting edges of which represent the two sides of a crown gear tooth space. The gear being cut rolls past the tools in exactly the same manner as it would roll with a crown wheel. During the generating motion each tool cuts alternately towards the apex point, thus giving the correct tapering tooth profiles. The generating roll may be obtained either by means of gearing or

alternatively by means of a master sector representing the gear being cut, which meshes with a master length of crown wheel representing the tools. After each cycle of the machine the cutting tools are withdrawn and the gear indexed one pitch, after which the next tooth is cut.

For large bevels, the former type machines are used, in which an ordinary planing tool is caused to develop the correct profile when under the control of a former.

Spiral Bevel Gears.

There are several types of bevel gear. There is conventional straight bevel gear, in which the teeth all converge to the apex point; helical, in which the teeth are arranged in the form of a true helix. There is the curved spiral bevel gear in which the teeth are formed as arcs of circles, and there is a spiraloid bevel gear in which the sides of the teeth are all tangential to a circle concentric with the apex point.

Helical bevel gears are formed in a similar manner to straight bevel gears, but during the passage of the cutting tools across the wheel face the blank is given a rotary movement. The more commonly used type of bevel gear has curved teeth, these being produced by a rotating milling cutter carrying angular blades.

No doubt you are all quite familiar with the Gleason machine using this type of cutter. The roll of the gear blank during cutting is similar to the roll of a straight bevel gear, but allowance has to be made for the fact that the profile on the cutter used for the curved spiral gear must be sufficiently thin to pass through the spaces of the small end of the bevel teeth, and as the same cutter teeth have to generate the wider spaces of the large end of the bevel teeth they have to be arranged to sweep through a larger space at this end, in order to cut out the necessary material.

Machines at various times have been developed for the hobbing of bevel gears. One of the chief troubles of bevel gear cutting is the fact that it is necessary to index the blank after each cycle. This not only is a source of inaccuracy, but also increases production time. One of the chief advantages of the hobbing machine for spur gears is that the motion of hob and blank is perfectly uniform. In the case of spiral bevel grears a certain amount of success has been obtained, but whether such machines will in time displace the conventional indexing machine remains to be seen.

I should like to express my thanks for the loan of photographs and slides, from Messrs. Burton, Griffiths & Co. Ltd., J. Parkinson & Son, J. Holroyd & Co. Ltd., and Alfred Herbert, Ltd.

Discussion.

MR. F. W. SHAW: If someone else had opened this discussion I am sure that one question he would have asked would have been about the poor work we get from hobbing in comparison with the fine work from the Fellows' gear shaper. Now, whatever be the type of machine, we get both good and bad gears from it; we get just as good gears from any of the different machines. That, at least, is my opinion, based upon experience.

The lecturer stated, or inferred, that generation on the Fellows' machine is continuous, but is not so on the hobbing machine. That is not quite the truth. There is such a thing as feed on the Fellows' machine, and although, as Mr. Eatough said, that feed is in the control of the operator, so long as there is some feed, flats, and facets, or rather lines of a definite width, depending upon the form of the cutter teeth, will be seen along the profiles. It can be admitted, of course, that hobbing is not quite continuous so far as generation is concerned because the hob is a discontinuous worm—discontinuous because it needs gashes to provide cutting edges. At the same time, the case is not as bad as it looks; moreover, by those who know how, some of the difficulties can be avoided. A well-known Huddersfield concern has hobbing machines by which the facets are eliminated by traversing the hob endwise (tangentically) as it feeds across the blank, this tending also to improve the accuracy of the work because the cutting edges are continually changing their action as the hob passes across the face of the blank, an important point where the hobbing time extends to a week or so.

In dealing with the form of the hob thread, Mr. Eatough said that the normal section should be that of corresponding elliptical gear, but that, since that would be awkward, the form is made that of a tooth of a gear of the maximum radius of the ellipse. That is not, in my opinion, the correct design for a hob. A hob in its transverse section, that is, the section at right angles to the axis, should be an involute helical gear.

Worms of that particular form for use in worm gearing were originally patented although they are only simple helical gear.

Now, nearly a hundred years ago a certain professor suggested lapping, but as an aid to correct lapping he suggested the endwise traversing of the pair of gears as they ran together, the one forming the lap for the other. He also mentioned that each gear shaft should be provided with a heavy flywheel so as to maintain uniformity of motion while lapping is proceeding. Among modern lapping machines there are the Fellows and other systems in which lapping is done

with a helical gear of such a helix angle that when in contact with the wheel being lapped the axes of gear and lap are crossed. The work is traversed in the line of its own axis across the lap gear. But even this system is dependent for its success to a great extent upon the lap supplied, which, I understand, has about a hundred times the abrasive resistance of most metals. Thus the lap wear in lapping a single gear is exceedingly small and on account of the motion to which gear and lap are subjected the lap teeth tend to maintain their initial sectional shape. By the crossing of the axes is avoided the pure rolling, non-abrasive action that would otherwise exist at the pitch lines.

MR. CROOKE: Production engineers have machines of various types at their disposal and the trouble seems to me to be that the firms who use these machines think they will go on for ever like the rolling stream. There must be a useful life for all types of machines, generating or otherwise. I believe we are all cursed with noisy gears at some time in our experience. Whilst it is admitted there are really good practical men who are capable of producing gears to such accuracy that they should run perfectly satisfactorily, they do not run quietly when the gears are assembled. It is principally due to the fact that designers of the different types of plant or machinery do not realise the importance of strengthening sufficiently the shafts on which the gears are mounted, and possibly the bearings have insufficient capacity to carry the load transmitted through the gears. In our own particular branch of the industry we can get trains of gears running, in my own opinion, very well, at certain speeds of the machine, but as the speed of the machine varies, so the sound from the gears varies, but more than one would expect from the variation of speed. No doubt this is due to certain torque reactions which are taking place in the machine over which the poor fellow who is cutting the gears has no control. It seems to me if designers of machinery in which gears are used would use their brains as much as designers of the gear cutting machines, the producers of gears would have far less trouble than they have at the present day.

MR. EATOUGH: I must stand corrected as regards hobbing. My reason for not going into that in detail was that I did not intend to lecture on hob design but just to give something that would be easily assimilated. Actually what you have said is perfectly correct. Regarding gears cut on the Fellows and rack cutting, I agree that this is in the form of facets and is under the control of the operator. Furthermore, means are provided usually, particularly in automobile gears, for smoothing out the facets by burnishing or some shaving operation. Also another point, very few firms I have seen sharpen Fellows' type cutters correctly. The finish on the face part of the cutter should be as good as originally provided by

the makers on the tooth profile and it is astonishing the degree of finish and the quietness of the gears which can be obtained.

MR. CROOK: Has Mr. Eatough had any experience of lapping double helical gears which have no clearance in the middle of the gear? There was also a question about speed of lapping on Fellows' machine, and the speed of reciprocation.

MR. EATOUGH: Double helicals are usually a bit of a problem, and the only way to lap these is to run them in together in pairs with the pitch lines in different positions. Regarding speed of the lapping, I cannot tell you exactly what it is on the Fellows' machine as I have not the figures. Cutting or lapping is done during the oscillation and not by the rolling.

MR. ECKERSLEY: I should like the lecturer to elaborate on gear grinding as compared with gear burnishing, or lapping of heat treated gears, and the disadvantages and advantages, if any, of each method.

MR. EATOUGH: Provided you can grind a gear I prefer to grind it straight off, but that is necessarily expensive compared with lapping on high production work—preferable to lap on cheap makes of gears. In cases where you cannot grind the gears, lapping has to be resorted to.

MR. CROOK: With grinding you are concerned with surfacing indexing. Take surfacing of the tooth of the rack—lapping there is an advantage.

MR. EATOUGH: I agree. I think I might say that one of the most successful modern gear processes follows faithfully the sytem. It has only been done by the exercise of very great care and accuracy in the manufacture of the machine, etc.

A VISITOR: The best method of profile grinding is by the Maag method of rolling the tooth between the two wheels or break type which is done by a formed wheel.

MR. EATOUGH: There I agree in principle—the Maag machine is ideal—a very fine machine—but the other type of machine I did not mention is also very fine.

MR. PUCKNELL: Is there any commercial way for the grinding of bevel gears; alternatively, what is the best commercial way in which to deal with heat-treated bevel gears after cutting?

MR. EATOUGH: I do not know the machine on the market for grinding bevel gears although there are several machines in existence.

A VISITOR stated that he was experiencing trouble with a hob which had been passed by the N.P.L. and asked for an explanation.

MR. SHAW said it was difficult to give an opinion without going into the whole thing. He strongly suspected the hob. The speaker said he should not suspect the hob, and Mr. Shaw said it might be a hundred and one things. The speaker than said it only occurs on

helical gears and he did not find it on spur gears. He wondered if it was due to the faults formed during hobbing.

Mr. Shaw's conclusion was that there was no theoretical reason for the trouble outlined, but it was not the facets mentioned.

MR. OWEN: We have heard a lot about the production of relatively small gears but nothing about big gears. One is a little disappointed in that the lecturer has only referred to very small gears, although it was mentioned that the lecture would deal with the manufacture of gears for general purpose. It seems to me the whole of the lecture has dealt with the manufacture of gears for a particular purpose. The manufacture of big gears entails enormous cost in plant, whether it is written off in five, ten, fifteen, or thirty years. It is these problems which matter to you as production engineers.

MR. F. W. SHAW (after further discussion): In reply to the gentleman who has expressed disappointment concerning the limited scope of the lecture, may I interpose a word on the subject of the larger gears? Some years ago my attention was drawn to a very serious error in certain turbine gears, disclosed after the gears had turned a short time. On the large wheel appeared forty lines right across the face. I do not know whether you understand what I mean, but when the gear was viewed from a distance, there appeared to be forty bright lines equi-spaced around it. The gears were noisy, of course.

We could not trace the fault to any error in the hob, nor to error in the dividing wheel. Then we subjected the worm to examination but found the thread in good order. The whole trouble was finally traced to end play in the worm—to so-called cam action. The end faces of this worm must have been out of square ever since the machine was built, yet on that very machine had been cut hundreds of turbine gears, some of which had been known to cause trouble upon being installed. The fact of the worm being triple-threaded and the dividing wheel having 120 teeth accounted for the number (40) of bright lines. There were, of course, 40 cam actions at each turn of the dividing wheel.

MR. PUCKNELL: I gathered from something that Mr. Eckersley said in discussion that what we have to do in the production of commercial gears is to make these gears as theoretically sound as possible and then, by means of grinding or lapping, make them as commercially acceptable and correct as possible. In other words, we spend our time trying to produce them theoretically correct, and then by some other means commercially acceptable.

The design of the housing or box in which the gears are to be placed and run is very largely to blame for the noise which we finally get. We produce gears which on the noise test are made

very good and then we put them in a box, run them in and find the box acts as a microphone, so that the time we have spent in the efficient production of the gears in the first place is apparently thrown away when we have to correct the gear which is to be noiseless in its own housing.

MR. EATOUGH: Yes, I quite agree.

IMPROVEMENTS IN THE PRODUCTION OF STEEL.

Paper presented to the Institution, Birmingham Section, by Josiah W. Jones, M.Sc., & N. I. Bond Williams, B.Sc.

A FAMOUS statesman from Birmingham, Mr. Joseph Chamberlain, advised his generation to "Think Imperially." The present Vice-Chancellor of the University of Birmingham, Sir Charles Grant Robertson, addressing a gathering of "freshers" some years ago said, "The function of a University is to train men to think independently." An old proverb which has lived in various forms through the years recognised the powerful influence of thought on the man himself—"I think, therefore I am." These sentiments challenge the modern engineer to "Think Metallurgically." No longer are his constructional materials just brass and iron but a range of several thousand products of metallurgical practice to which important additions are made every year. The fullest advantages of the materials can only be taken where there is some knowledge of the sciences which confer the improved qualities. Addressing the 1936 meeting of the British Association, Sir Josiah Stamp said: "If the impact of science brings certain difficulties, they can only be cured by more science. *Ordered knowledge and principles are wanted at every point.*" It is doubtless in this spirit that your Committee have requested a paper on Improved Steels, and no apology is made for introducing such details of metallurgical practice as are necessary to explain the advantages accruing to the engineer in the correct use of the new materials of construction.

Changes in methods of production of steel fall naturally into two classifications: (1) Improvements considered so by the maker; (2) improvements considered so by the user. These two interests are closely associated. Some five years ago, when reading a paper* on a similar subject the author drew attention to the influence on steel making practice of the principles of production to attain the desired end of "more steel per hour." Improved outputs have resulted from the measurement and analysis of the "time factors" of the various operations, both mechanical and chemical. Machines have displaced manual labour and more scientific selection of

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constructional materials and methods have given increased life to the furnace and working parts with benefits analogous to improved tool life.

Arising directly and indirectly from this control to obtain a greater output, there has followed improved qualities of the steel, thus maintaining the close analogy with engineering practice that scientific production has yielded increased outputs and improved, not inferior, qualities.

The needs of the mechanical and structural engineer have been catered for by the production of high tensile steels making possible an increasing reduction in the ratio of weight to horse power and by the supply of ever-increasing types of corrosion-resisting materials.

While he is interested in such developments, the personal need of the production engineer is for a uniformity in the material he has to forge and machine, and a supply from day to day of exactly the same material. *Only in such conditions can the sequence of operations and the design of tools be brought to their most efficient state.* In some measure this is the contribution which steel makers are seeking to the offer to your Institution and only those highly trained in the science and practice of the process can appreciate the difficulties in the way.

Steel-Making Processes.

It is generally conceded that the details of the process of steel manufacture has a material influence on the product. Five different methods are practised, *i.e.*, crucible, Bessemer, Siemens open hearth, and electric furnaces (*a*) arc, (*b*) induction. The order represents the sequence of historical development and, with the exception of crucible steel, which has a tradition of reliability all its own, is the approximate order of quality. The question of quality, however, is a thorny one and a return will be made to it. Each type of steel may have particular qualities adapting it to a certain process and in this case quality is largely a matter of uniformity of properties and supply.

The large bulk of carbon steels and many low alloy types are products of the Siemens open hearth furnace, in which steels are made in masses varying from 50 to 250 tons at a time, while auxiliary furnaces may hold some 500 tons of molten metal. The handling of these huge quantities of liquid metal at temperatures from 1,400° to 1,800°C. calls not only for scientific knowledge but also vast experience and collaboration between the metallurgist and structural engineer. These furnaces are fired by gas and air, both preheated by waste gases in order to attain such high temperatures, and the problems associated with the operation and maintenance of one of these furnaces with the auxiliary equipment of gas making plant, control valves, preheating chambers, overhead cranes, and charging

machines, make the lot of the steel maker no easy one. That progress has not been rapid since Siemens made the first furnace in 1868 is not surprising and recent developments reflect great credit on those responsible for them.

Valuable assistance to the steel maker has come from a new direction, the electric furnace. Two types are in use converting electrical energy into heat, (*a*) the " arc " type, and (*b*) the newest comer, the high-frequency induction furnace. In the former, heat is radiated on to the contents of the furnace from an arc, struck between carbon electrodes or between such electrodes and the bath of metal to be refined. These furnaces have an average size of 15 to 25 tons and the smaller mass of metal, the simplicity of operation, the high temperatures available and controllable, give new opportunities to the steel maker. Purer steels, close control of chemical analysis, and improved facilities for casting are available. Thus, highly alloyed steels (e.g., stainless steels, high speed steels) can be made, which in the Siemens furnace it would be difficult to do, and in some cases impossible.

The high frequency furnace approximates closely to the ideal means of making high quality steel. The raw materials are charged and heat for melting is generated in the metal itself by means of electrical energy of high frequency alternation induced by a magnetic field set up by primary coils, water cooled, which surround the furnace. The metal is actually hotter than the refractory in which it is contained. Automatic mixing, due to eddy currents, assist in the diffusion of constituents, decrease the time for the process, and promote uniformity of analysis. With such a furnace the melting and alloying operations can be carried out in a vacuum and steel prepared without contamination of gases. At present this is not generally considered necessary.

It is difficult to make more than a general statement concerning the types of steels produced by a particular process since practice will vary with different manufacturers. Structural steels produced in large quantities are mostly from Siemens and Bessemer processes, basic for mild steels and acid for higher carbon steels of the 40/50 ton types. High carbon tool steels are largely products of the crucible and electric furnace.

Defects in Steels.

The ideal constructional material will have a uniformity of structure and consequent absence of directional weaknesses. The greatest difficulty in producing a steel which will be satisfactory to the engineer is to secure this uniformity of structure from outside to centre.

Most steel starts life as a cast block of the order of 3 to 10 tons. As this casting passes from the liquid to the solid state, the temperature gradient from the chilled outside to the central liquid promotes

selective freezing and the outside tends to be of different chemical composition and crystalline condition to the neighbouring and more interior layers. By the time this large casting reaches the machine shop or forge as bars, sheet, billet, etc., these variations in structure have been modified and extended by the rolling and forging practice. The steel maker minimises these defects by cutting off and discarding portions from the bottom and top, often amounting to one third of the bulk, and by machining the surface for the removal of blemishes in the skin. All steel for forging and/or deep pressing should be subjected to a microscopic test by deep etching with suitable acids. Such tests are simple to apply and require no elaborate apparatus. but deductions from them do need considerable experience in each particular class of work. It is much more satisfactory to use available tests to reject material before processing than for the processing to act as its own test. That this subject merits attention when discussing improved steels is shown by the consideration given by steel makers.

Since 1924, the Iron and Steel Institute and the British Iron and Steel Federation have directed the work of a central committee under the chairmanship of Dr. W. H. Hatfield F.R.S., and several sub-committees to explore the causes of heterogeneity in steel ingots. The results of this work have been published in some six reports. Details are outside the survey of this paper, but studies of the influence of casting temperature, design of moulds and deoxidation practice have yielded such results that modern steels should be free from *excessive* heterogeneity and localisation of impurities.

When steel is made and cast in smaller quantities as in crucible and electric furnace practice, these defects and the presence of non-metallic inclusions are naturally reduced to a minimum, and practice is further profited by knowledge gained in studying the improvement of larger ingots.

[At this stage films were projected showing the following operations in modern steel making: *Melting of stainless steel in electric arc furnace, casting of stainless steel, working of ingots, high frequency shop (general view) (motor generator shop), charging and starting high frequency furnace, slagging, chemical tests, tapping furnace, teeming ingots, stripping ingot moulds, weighing ingots, ingot stock yard, planing ingots, pre-heating furnace and soaking pits, cogging mill, cutting and weighing discard, hot saw, forging test piece, turning round bar, billet mill, cooling billets, physical and chemical tests (Brinell tensile, deep etch, sulphur print, inclusion count), combustion carbon content, final inspection, signing of release certificate, and forging of crankshafts.*]

Routine of Steel Making Processes.

The practice in the crucible and electric induction furnace is distinguished by the fact that steel is made by melting together

the relatively pure materials, wrought iron, carbon, and alloying elements required to give the desired chemical analysis after casting. All other processes are complicated by the fact that the raw material consists of " impure iron " known technically as pig iron. Comparative compositions are indicated by the following typical analyses :

	Pig Iron	Steel
Carbon	3.5%	0.45%
Silicon	2.0%	0.3%
Manganese	0.4%	0.7%
Sulphur	0.1%	0.03%
Phosphorus	0.8%	0.03%

It will be recognised that the same constituents are present in each case, only the relative proportions being different. Fame and fortune yet await the scientist and technician who can produce as a primary product from the smelting of an iron ore, a metal with its elements controlled to the requirements of steel. At the moment the pig iron is the best basis available, and from it the steel maker must extract the undesirable excess of each constituent. To do this, high temperatures are necessary, 1,400°C to 1,800°C, to liquify the mass, and oxygen is added which reacts with these elements to form either fused products SiO_2, MnO, P_2O_{50}, which rise to the surface as a slag or gases CO, SO_2, which bubble off, and so are removed from the steel.

Unfortunately the process is not as simple as can be stated. The proportions of constituents are reduced to less than that desired and an excess of oxygen accumulates, present in the steel as dissolved iron oxide. While this oxide is useful as a purifying agent, its presence in the finished steel impairs all useful properties. Removal may be effected by a controlled addition of carbon, which removes the oxide at a rate increasing to a maximum at the point of solidification

$$FeO + FeIC \longrightarrow W3Fe + CO \text{ (gas.)}$$

Steel so made intentionally is called " rimming steel. " Though the ingot has a number of localised blow holes, they have non-oxidised surfaces and weld up during forging. This steel has a place under the title of this paper as it has been developed to meet the demand of the engineer for " deep drawing stock." An alternative and more general method of removing the excess iron oxide is to add an element which has a powerful chemical affinity for oxygen such as aluminium, vanadium, silicon, titanium. These are termed " deoxidisers."

$$2\ Al + 3FeO \longrightarrow 3Fe + Al_2O_3 \text{ (solid)}$$

The fact that this compound is a solid means that while some part rises to the surface and is floated off, the largest part formed during cooling and solidification, becomes part of the structure and has

an influence on mechanical properties in keeping with the general rules of relationship between microstructure and mechanical properties.

These facts may be stated in a less technical language. In order to manufacture steel from the raw material pig iron, carbon which is in excess of that required in the steel must be reduced, and the proportion of other elements also altered. Modern research is showing that the manufacturing conditions are producing an effect in the crystalline structure which has not hitherto been appreciated. Changes in methods are responsible for alteration in structures, which in turn modify the properties and behaviour of the steel.

The Crystalline Structures and Mechanical Properties of Steel

The fact that a piece of steel failing from sudden shock often exhibits a large bright surface, gives rise to a general but false opinion that this crystalline state is a limited and undesirable condition. All metals, all the time consist of a conglomerate of small crystal grains. Metallic crystals are not intrinsically brittle, but yield and deform in a plastic manner during all rolling, stamping, and pressing operations whether hot or cold. Only pure metals and alloys of which the constituent elements are in mutual solution in the solid state have the simple structure consisting only of crystal grains. Most alloys and probably all steels have a second constituent, present in the structure, usually some form of carbide, which is by nature very hard and non plastic. The effect of the hard carbide on the matrix of plastic crystal grains is to " stiffen " the structure and increase the hardness, tensile strength, and yield point by offering resistance to flow. This is well illustrated by the time honoured diagram showing the influence of content of carbon on the mechanical properties of steels. It is desirable to emphasise at this stage that the major factor which controls the mechanical strength and shaping properties of the steel in the normal condition, is the chemical composition and crystalline nature of the conglomerate of crystalline grains which form the body mass of the steel.

It is common knowledge that the impact value of a steel is decided by the relative grain size. A mild steel (0.2% carbon) with a fine grain has an impact value of 82 ft. lb. Izod, and with a coarse grain 23 ft. lb. Izod, the tensile strength in each case being 22 tons per sq. in.

Causes of Variation of Grain Size.

The grain size of all metals at room temperature is decided by one of two factors : (a) in the case of a casting, slow cooling from the the liquid state produces a coarse grain and rapid cooling, a fine

grain ; (b) in a cold rolled or pressed shape, annealing at too high a temperature or for too long a time will produce a coarse grain.

While sharing these conditions with all other metals steels are controlled by additional phenomena. When steels are heated above a certain critical temperature, a new crystal structure is formed by an atomic rearrangement and grain growth proceeds from a fine to a coarse state as temperature and time is exceeded. The temperatures concerned vary from about 750°C. for a plain carbon tool steel to 925°C. for a dead mild steel but actual temperatures to give the best results will vary with the type of steel and makers will usually make recommendations. By this heat treatment fine grain size may be obtained in any steel (with the exception of certain highly alloyed types) by an independent and precise heat treatment. Such a refining operation however is always undesirable and often impossible. Hence the production of a steel which has a desirable grain size resulting from casting and rolling conditions and which will maintain this condition, during the sequence of metallurgical operations common to engineering practice, annealing, hardening, toughening, is a noteworthy development.

Research work in America during the last few years by MacQuaid and Ehn and others and more recently in the country by Swindon and Bolsover has directed attention to the factors which control grain size in steel and the fundamental influence of grain size on mechanical and shaping properties.

Factors Controlling Grain Size During Manufacture.

Reference has already been made to the routine of the manufacture of steel common to all processes. It has been shown that after the purification of the liquid iron and addition of alloying elements it is still necessary before casting to remove excess oxygen. This is done partially by the alloying elements themselves, silicon, manganese, vanadium, and titanium but the commonest element is aluminium. This element has been used for years to prevent gas formation during the solidification of the ingot so obtaining sound steel. Recent research has shown that, provided that the excess oxygen is controlled within certain limits and the necessary quantity of aluminium is added to the liquid metal before it solidifies in the moulds, then a fine grained steel is obtained. If no aluminium is added a coarse grained steel is obtained.

Thus two steels made in the same process, having analmost identical chemical analysis, have different structures and properties due to a difference of procedure in finishing. It has been possible in the past for a finishing practice to vary from cast to cast, and steels having identical chemical properties and tensile strengths are found to vary in their shaping and heat treating properties because they have

a different " inherent grain size." The function of the aluminium in restraining the natural tendency of the material to produce large grains is somewhat involved and will not be considered. It can be concluded that the steel maker is now able by control of the steel making process and deoxidising additions, to control the grain size of the steel and that he is now beginning to appreciate the importance of this property on the subsequent fabrication. The influence of reheating temperature on two steels may be identical in the composition and properties as included in an ordinary specification, but the conditions of making the steel have varied and they may differ in the compositions with regard to aluminium oxide and oxygen. Both undergo the critical change of structure to austenite at the same temperature about 800°C. but in the " coarse" crystal grain commences to grow at this temperature, whereas in the "fine" the grain growth is restrained until about 1,020° C. Most operations of forging, case hardening, heating for hardening and toughening, are carried out within this range 800° to 1,000°C and hence these steels will have different properties both in the range and after subsequent cooling.

System of Grain Size Control.

The American Society for Testing Materials published among their Standards 1933 a Grain Size Chart (E.19 33). Microsections of structural steels carbonised for not less than eight hours at 1,700°F. (925°C.), and slowly cooled to show pearlite were prepared at a standard magnification $\times 100$. From the photomicrographs eight classes of steel are listed from No. 1 up to $1\frac{1}{2}$ grains per square inch to No. 8. Ninety-six or more grains per square inch. Thus Nos. 1 to 5 (12 to 24 grains per square inch) are termed "coarse " grained, and Nos. 6 to 8 " fine " grained.

It will be noted that *increase* in the grain size classification number means a *smaller* grain size in the steel. Reference to the actual chart makes identification a fairly simple matter. Some suppliers will prefer to set up their own standards of reference. The United States Steel Products Co. (Carnegie Illinois Steel Corporation) classify three standards in each of four different types of steels :

Type A	approximately	3	to	6	grains	per	square	inch	Class	3
,, B	,,	24	,,	48	,,	,,	,,	,,	,,	6
,, C	,,	48	,,	96	,,	,,	,,	,,	,,	7

By the use of such methods and standards co-operation between steel manufacturer and engineer becomes possible, so that a supply of steel with the desirable grain size for a particular operation can be arranged.

Influence of Grain Size on Operations Involving High Temperatures—Hardening and Toughening.

Factors of interest are time of operation, warpage, quenching cracks, and depth of hardening. The success of reheating, quenching and tempering for hardening and toughening, has always been limited by the " mass effect " of the article, steels tending to harden to varying depths, and then to show black centre. The advent of some nickel steels tended to produce more uniform results, and increased the property of " hardening at depth." Experiments with controlled steels show that an inherent coarse grain size rapidly produces a coarse structure at hardening temperatures, and that such changes induce hardening at depth. Such steels will also have an increased tendency to warpage and fine microscopic cracks, causing impact weakness.

Fine grained size decreases the time cycle, permits hardening temperatures to be exceeded, and yet maintains impact strength and uniformity of result. In the past, failures have been experienced from the use of steels of both too coarse and too fine an inherent grain size, but it would now appear that experiment will reveal the ideal grain size for a particular section to produce simplicity of operation, maximum hardness and toughness, and minimum dimensional changes. All steels do not require the same depth-hardening properties. Fine steels will require complete hardening, while steels requiring resistance to shock will profit from the tougher centre of fine grained shallow hardening tools. Modern automobile construction is making increasing demands for a combination of these properties, surface hardness, high elastic modulus, and impact strength, due to increasing engine speeds up to 4,200 r.p.m. These properties are supplied by an efficient case-hardening practice, or by a steel hardened to such a depth that a core toughened, but not hardened, supports the surface. One of the oldest firms of English steel makers now supply carbon tool steels 0.75 to 1.30% carbon in all the usual sections in three distinct types termed: Shallow hardening, medium hardening, and deep hardening.

Case Hardening.

Coarse grained steel permits a quicker, deeper, and more even penetration of carbon, producing harder and more even case, but is limited by the greater tendency to crack, warp, and check on grinding. Fine grain effects more shallow hardening, but freedom from the above defects. An added advantage is that the absence of serious grain growth during the carburising operation permits a single quench direct from the box. The usual double quench is unnecessary unless it is desired to obtain super results. Types of the single quench steel are available for most purposes. Steels which would, and steel which would not carburise, have long been known.

In fact, good suppliers would always case harden a sample from each cast before dispatch. Again claims are made that simplicity of operation and uniformity of results are obtainable with superior properties, by the use of the correct grain size in the steel.

Forging.

At higher temperatures the large grain size tends to be slightly stronger than that of the fine grain, though the increase is of little commercial value. The larger grain size is found to be associated with sounder metal, and one which flows more uniformly, and produces forgings of greater density. The intermediate size in Carnegie steel, however, produces crankshaft forgings of greater toughness and torsional strength.

Influence of Grain Size on Operations in the Cold—Shearing.

Quite a short experience of this operation will bring to light the tearing and cracking at the centre, due to heterogeneity in the steel already discussed. The influence of the grain size is rather on the power required, and on the edge. Fine grain size is tougher, offers greater resistance to shearing, but shows a decreased tendency to crack at the edge. This operation assumes much importance in flash trimming of forgings or stampings for automobile connecting rods, front axles, etc. Fine cracks originating at this trimming are not seen, but develop on subsequent heat treatment. Such defects can be eliminated by the use of steel with the desirable grain size.

Machinability.

Makers of tool steels in the high frequency furnace claim increased cutting life for their products,* due to purity and uniformity of structure. No critical information is available on the influence of grain size on tool performance. The effect of grain size on steels to be machined fails to show outstanding direct advantages. Indirect but important effects are the smoothness of the machined surface of the steel with finer grain size. The author would suggest that a standardisation of any of the several factors deciding machinability will permit of the closest check of tool design on speeds, feeds, etc.

Deep Drawing of Steel.

The undesirable effect of large grain size in steel blanks for pressing and deep drawing, has received much attention of recent years because its presence is rendered very obvious by the roughened surface after the operation. Probably workers in brass have been most vociferous about it, since they have to produce after pressing

* *A. G. Robiette. Electric Melting Practice.*

a uniform electroplated surface. Compromise is necessary for best results. Larger grain sized steel is softer and less springy, and will produce a desired shape more effectively if the deformation is not excessive. Where deep drawing is necessary a finer grain is desirable to avoid the rough orange peel effect on the surface of the article. All the difficulties of these operations are not confined to the metal. There is a great art in the design of dies and presses, to apply the pressure correctly with regard to position and intensity, but machines are outside present considerations. Intermediate low temperature annealing operations risk a possibility of local patches of large "exaggerated" grain growth due to a critical state of strain. Full annealing or normalising by heating above the critical range is necessary to produce full softness, absence of hard spots of hard carbide and uniform fine grain size.

Additional phenomena causing variation in the properties of drawing qualities of steel sheet is "strain ageing." This effect appears most critically after an elongation of 1.5 to 10%. After cold rolling the properties of the steel change with time and conditions of temperature during storage. Changes in properties of cold rolled mild steel :—

	Prompt	Two months	Six months*
Yield point (tons per square inch)	11.8	12.65	12.6
Net strength (tons per square inch)	19.3	19.65	20.2
Elongation (% on 2 in.)... ...	44.3	39.10	40.5

These changes are associated with small properties of carbon, nitrogen, and oxygen, which indurdually have a decreasing solubility with temperature, and tend to precipitate out from solution, and so decrease the plastic nature of the crystal grain structure.

	Temperature °C.	Solubility %
Nitrogen	580	0.5
	Room	0.01
Carbon	700	0.04
	Room	0.006
Oxygen	715	0.11
	Room	0.05

Oxygen is probably the most powerful direct and indirect factor in producing this increase of hardness and brittleness with time. Since the deoxidation conditions which control grain size are concerned with the reduction of the oxygen content, some definite

*H.M. Cox. *Metal Progress, September, 1931, page 85.*

improvement, that is, uniformity of properties and absence of change with time are also noted with these steels.

The Quality in Steels.

Until the advent of some modern electric steels, it was always the custom to specify for an exacting job either tool or crankshaft, a steel made in the crucible. Even to-day it is a safe procedure. The steel made by this process from pure raw materials, is said to have more " body." This indefinable property probably includes a high ratio of yield stress, elongation, and toughness to tensile strength. It certainly includes an absence of localised defects, and some latitude in working, and uniformity of qualities. Its uses have been limited by the fact that only some 80 lbs. of steel can be produced in a single operation, but it has set a standard to which other processes of greater production may attain. The development of the high frequency furnace for steel manufacture has increased production of a material of such high grade, especially when carried out under such conditions of control and inspection as shown by the film. The absence of this quality of " body " shows itself in three aspects :—

(*a*) *Test House.* Here the steel fails to conform to *all* the conditions of the specification, i.e., tensile strength and impact value, or yield point and elongation. The difficulty is made all the more trying by the fact that materials having the same chemical composition, behave differently. A consignment from one source may always be satisfactory, while from another source it is sometimes satisfactory, and sometimes just fails.

(*b*) *Processing.* Although satisfying the test house, a material may be subject to *intermittent* failure, particularly where considerable plastic deformation by forging or deep drawing is necessary.

(*c*) Finally there is the incipient failure which passes inspection and assembly, only to appear with a red face in the service department. Such things have been known to happen.

In a few cases the specification is at fault. The substitution of a low alloy for a straight carbon steel will remove the trouble, but in most cases it is more deeply seated. Change of chemical composition may effect relief, but it is only of a temporary nature, and the intermittent trouble appears more potent than small changes of chemical composition, which decided the heat treating and shaping properties.

Modern research suggests that this factor is the " inherent grain size " or " austenite grain size." This is decided by the steel making conditions, and by details of composition not normally specified, i.e., oxygen content and alumina content.

Control of the inherent grain size by the steel maker promises to be a solution to many of these metallurgical problems associated with production, provided that such steels are used with under-

standing. The same article produced by two different sets of dies may require a different grain size in each case to produce the *best* results, but a constant supply of a fine grained steel will be better than a supply which varies over a wide range from week to week. The smoother the production practice, the less likely are failures to appear in service.

A material with slightly improved properties, and which behaves the same in forging, heat treatment, and machining operations from consignment to consignment is an attactive offer from the steel manufacturer to the production engineer. Such are the suggested advantages from the control of the inherent grain size of the steel during manufacture and co-operation with the engineer to supply the grade most suited to his needs.

Improved Methods of Fine Inspection.

The failure of a material from stresses less than that of the natural strength is due to either : (*a*) internal defects which are of such a relative size as to decrease the effective sectional area or (*b*) surface defects, usually fine cracks. Owing to the inevitable heterogeneity of large masses of steel, much consideration has been given to the development of non-destructive tests in the finished or semi-finished state, for the presence of such structural weakness. Of many suggested the following are worthy of comment :—

(1) *X-Ray Shadowgraphs.* These are used to an increasing extent on important forgings and welded parts, such as used in railway and marine engineering.

(2) *Magnetic Detection.* The article under test, e.g., a steel rail is passed through a standard magnetic field and variations in structure produce a variation in magnetic flux, and these changes are indicated on sensitive recorders. Correlation of effects with position of test piece indicates position of defects.

(3) *High Frequency "Sound" Waves.* The transmission through a piece of metal of sound waves by tapping on the reverse side has long been used as a test for "soundness." From German sources a new method has been developed whereby high frequency vibrations are imparted to one side of the metal. On the opposite side a film of suitable liquid covers the metal, and any local conditions in the interior are indicated by visible effects forming a pattern on this surface of the liquid.

(4) *Magnetic Detection of Surface Cracks.* The presence of very fine cracks in the surface has long attracted the attention of the physical metallurgist, owing to its critical importance.

The intensification of stresses on the infinitesimally small area at the end of the crack causes its rapid propagation through a crystalline material. The visual detection of fine cracks on the surface by the microscope is attended with many technical diffi-

culties, and is of little use. A magnetic method now used with much success for the inspection of parts for aero engines consists of magnetising the steel under inspection. Fine iron dust either dry, or suspended in a suitable liquid, is then poured uniformly over the article and the iron particles mass over any cracks due to local intensity of magnetic flux and so exaggerate the size of the crack, itself invisible. There are definite conditions of operation to make the test effective. Apparatus and particulars are available from well known suppliers.

It is a fair inference that in many causes of failure where a post mortem examination cannot reveal exactly the cause, that a fine crack on the highly stressed surface has initiated failure from fatigue. The production of such cracks is attendant on every stage of heat treatment and processing.

Such inspection is a guide to the choice of material and methods of shaping in which these defects do not arise. It would be difficult to give an estimate of economies to production and the reliability effected, if no fine cracks were initiated at any stage in the manufacturing process.

The Trend of Improvements in Steel Production.

During the present century the considerable developments in transport engineering have resulted largely from the use of stronger, lighter, and more reliable constructional materials. and many branches of engineering have benefited, if to a less spectactular extent.

The new steels have resulted from the addition of a number of alloying elements and an understanding of their properties when several elements are used together. This trend will continue, as shown by recent information about copper phosphorous chromium steels, and always there will be the possibility of some discovery like the nickel aluminium magnet steels.

A feature of the achievements discussed in this paper is that they are not attained by the addition of new alloying elements but be taking *advantage of properties already existing but hitherto unappreciated* in the plain carbon steels. Scientific exploration has demonstrated the relationship between crystalline structure and mechanical properties and a means of controlling the type of structure has provided a method of making a satisfactory steel. Particularly are the properties during shaping and heat treatment concerned and so the manufacture can be designed as a beneficial rather than a detrimental influence on processing and service. This knowledge has been gained as a result of co-operation between the research metallurgists and the engineer, since no experiments in a laboratory can reproduce exactly the conditions obtaining during manufacture.

The properties of the material to be shaped must always place a limit on the enterprise and ingenuity of the production engineer. The scientist has demonstrated that detailed attention to the crystalline structure of the material is well repaid by increased facilities for shaping, but this desirable end can only be achieved by mutual understanding and co-operation between the maker and user of steel.

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Discussion.

MR. E. P. EDWARDS (Section President, in the chair): We have had an absorbingly interesting paper this evening, one of the most interesting papers, I think, we have ever listened to in this hall. The subject is one which affects our daily interests, and I am sure we all of us have problems we might discuss with the lecturers. The question of grain size, which has been very largely gone into by Mr. Jones, is a particularly interesting one. It seems to me that we are approaching something like Utopia, when we shall just tell the steelmaker the size of the grain we want in our steel and then go home and just leave our operators to machine the materials, and finally collect the profits at the end of the year! All the same, it is very interesting to hear of the effect of grain size on the structure of various materials.

MR. H. F. SPINKS: When you get surface cracks in carbonised mild steel, do they go very far beyond the skin? Do they generally go actually into the soft core?

MR. BOND WILLIAMS: Answering the President, I do not think there would be any difficulties at all put in your way by the use of a smaller grain steel, providing of course that the grains are not so small that you need extremely large powers to squeeze the metal into its ultimate shape. That is what happens when grain size becomes excessively small, the metal becomes much more difficult to work, but I think, in the grain size that would be recommended by the steel makers (and which we should like to recommend) that it would not give any difficulty at all.

MR. JONES: Answering the question about surface cracks in carburised steel, the surface cracks themselves are probably very shallow indeed. The trouble with surface cracks is this, that they do not stay there. It is the peculiar property of a crystalline material that once you have a crack on the surface, any surface stress imparted to the material becomes highly concentrated at the very small area at the end of the crack. Therefore it becomes an intense stress at the end of the crack which rapidly propagates through the crystalline material. In non-crystalline material the crack goes so far and stops, and you have got to have a critical stress to get any further movement, but in crystalline material a crack, under stress, rapidly propagates right through the whole section until it meets with some local hindrance, so that surface cracks are none the less dangerous because they are only surface.

MR. L. W. WADDELL: I think Mr. Jones has laid himself open to a good many complaints which he might not have had if he had not given us his lecture. He stresses every trouble that is likely to arise

as being due to grain size alone, and not due to the way in which the material has been manipulated, particularly this last complaint about surface cracks. I am afraid the gentleman who raised the question will be saying straight away, "The steel we got was not correct grain size and therefore it has cracked," when the probabilities are it is their own grinding troubles alone and not the fact of the steel being wrong at all. The same remarks apply to a good many forging troubles; if the steel cracks in forging it is not due to the grain size but to the way in which the forger has treated it.

MR. JONES: I did want to leave time for the questions, so that I did not have time to make the acknowledgements which I wanted to make to quite a list of makers of English steel and American steel, and to Dr. Jeavons of Messrs. Lucas, Ltd., for the actual specimens which are on show.

One must agree with the questioner with regard to wrong manipulation producing cracks in the material, but what we are saying is that whereas a certain manipulation will not produce a crack in a material and another manipulation will, the second manipulation which produces the crack might be a quicker method of doing the job. Alter your grain size and you will not get the crack on the more efficient method. Grain size control will give you a latitude in some cases, and where you are using a carefully, experimentally determined grain size control and you are not producing cracks, you can be quite satisfied that your process is as efficient as it can be in our present state of knowledge, and I venture to suggest that in many cases a process so determined will be infinitely more efficient than one in use at the present moment, where you are getting coarse grain size one day and a fine grain size the next, though both the engineer and the steelmaker may be quite unconscious of the real trouble.

MR. J. C. EDWARDS: May I ask the lecturer if the initial difficulties in the manufacture of nickel magnet steel have been quite overcome: whether the manufacturers can now guarantee steel having given magnetic qualities?

MR. JONES: The nickel-aluminium magnetic steels are now produced in the high frequency furnace. They come into part of my chapter. Without the high frequency furnace it is doubtful whether that wonderful steel could be made, With regard to the difficulties in manufacture and qualities in steel produced at the moment, I I am sorry, it is one of the many things I don't know.

MR. A. MCNAB: I must congratulate Mr. Jones and Mr. Williams on the excellent paper we have heard. It will certainly provide me with an excuse for several difficulties I have to cope with. I am very interested in the grain size of steel. I was also interested to see how the grain size is achieved. I think I am right in saying that Mr. Jones said aluminium had a great effect on it. I have always

understood aluminium to be a deoxidising agent. In his remarks Mr. Jones did say something about some of the aluminium being left in the steel, and this having some effect on the grain size. I should like to know in what form this aluminium is left in the steel, if at all. We production engineers do not often get anything for nothing, and I would like to know the extra cost that this grain size control means in the price of the actual steel. One of the reasons why I have been interested in grain size is its effect on die blocks for forging; where you require a steel having the power of depth hardening, and also high impact stress. I should like Mr. Jones to advise me, if he can, what grain size would be applicable to that particular requirement. Also, is the effect of cold working, or working to below the critical range of the steel, destructive to grain size? Does the grain size still persist in the fine grain steel, say size 6, or is the grain size destroyed, for example, in the flash line of a stamping where it has been extruded between dies and you get, probably, a working temperature below the critical temperature? I should also like to know whether grain size can be obtained in both acid and basic steels.

MR. WILLIAMS: In regard to this question, first of all aluminium is a deoxidiser in steel. In steel practice it is customary to use two main deoxidising agents, aluminium and manganese. The manganese forms manganese sulphide. The majority of that goes out in slag, a small proportion is left behind in the steel which in itself is plastic. The aluminium, on the other hand, forms, as the speaker said, aluminium oxide, the majority of which would leave the metal in the form of AlO_2O_3, but owing to the fact that aluminium is added actually on casting, when steels are cast (I do not know whether the speaker has seen it in operation) the steel is poured from the bottom of the ladle, the aluminium is added at the same time, and some of that AlO_2O_3 is entrapped in small particles. Further reaction between the aluminium and oxygen in the steel is caused at the point nearest solidification, so consequently the AlO_2O_3 formed has no outlet to escape very quickly. That would leave a number of very small particles which are particularly noticeable, I believe in quick cooling steels. They, I believe (I am not sure of the mechanism there) form nuclei which are responsible for this small grain size.

As to the cost, I am afraid I cannot give you any information on that at all. As we have pointed out, we are not connected with industry and consequently do not know very much of these particularly intricate details.

With regard to die blocks, it depends mainly on the size of the dies to be used. It would be very difficult to lay down the grain size for a die block to be used, for instance, for making the gold link for a watch chain, or something of a very much larger order, such as a

car body. It does depend very greatly on the size of the article to be treated, for the depth of hardening would vary as the size of the work in hand.

Regarding the effect of the cold working, or working below critical temperature, the grain size would tend to persist in a material such as the flashing which is extruded between dies. It might be possible to get exaggerated grain growth, but the body of the metal which is actually left in the die, the metal which is of importance to the manufacturer, would certainly still persist in the same grain size. The flashing itself, although it could have an exaggerated grain size towards the outside, actually fairly near to the metal where it actually joins the forging, has almost certainly persistent qualities, probably very much the same, and I think that answers that point.

MR. MCNAB: May I put it this way. The grain size having been destroyed approximately $^1/_{16}$ in. from the actual body of the forging, would the heat left in the stamping be sufficient, provided it was above the critical point, to restore the original grain size, or would it be an indifferent grain size?

MR. JONES: I find it rather difficult to follow that question. One must distinguish between cold forming and hot forming. Cold forming followed by annealing does tend to give an exaggerated grain growth. Are you arguing cold or hot forming?

MR. MCNAB: Hot forming. The point is that sometimes I have observed the flashing to be so thin that it goes cold and is below the critical temperature at the end of the forging operation.

MR. JONES: In that case the answer is perfectly clear. You are forging at a high temperature, white hot. The flash cools down but the steel still maintains its fine grain size at the high temperatures and retains that fine grain size on cooling because there are no conditions in hot working which will cause an increase of grain size on cooling. That is to say your fine grain size will still tend to give you absence of cracks as shown on the diagram, quite apart from the influence of cooling on the flash. Grain size can be controlled in both acid and basic steels.

MR. E. T. COOK: It is difficult to discuss critically matters which we do not come across in everyday life, and all we can do is to try and appreciate the value of the work which has been put at our disposal to-night, and to put forward some of our individual problems, hoping for their solution by the lecturers' kind assistance.

One thing I should like to know is (it will perhaps be necessary for one of the representatives of steel firms, if there are any present, to answer this) can we, when we specify steel to-day, say for the manufacture of gears, couple with the specification a statement as to the grain size we want? I appreciate that it is unfair to ask the lecturer that question, but there may be somebody else who

can answer it. There is also a little problem which has always rather worried me in connection with the manufacture of springs. If it comes within the scope of this lecture perhaps Mr. Jones can advise me. In manufacturing flat springs say from sheet steel .020 thick having a .6 to .8% carbon content after the usual heat treatment process it is often necessary to adopt some commercial means for protecting the steel from rust.

One seems limited to a process which does not include plating. If one could protect these springs from rust by plating them it would be a very desirable state of affairs, but in practice I find we cannot do it. They become very brittle and the spring breaks.

One other question I should like to ask is, I have in the past been accustomed to take a piece of steel, nick it across, and break it with a view to judging for myself firstly the correct hardening of the steel, and secondly attempting to form an opinion as to the suitability of the steel for a particular job. There is no question of taking microphotographs but simply examining with a magnifying glass the grain of the fracture. It appears to me to be a very useful guide. Is it the opinion of the lecturer that we should continue to use this method for instance, in steels such as magnet steel or tungsten tool steels? I find that the magnetic properties are linked up with the structure to an enormous extent. Perhaps the lecturer can explain that very fine, silky structure which we see on properly hardened magnet steel. It appears to give one a guide to the correct treatment.

MR. JONES: Can I order from the steelmaker steel of a definite grain size? If you write to Mr. Carnegie of Illinois, yes. I have an idea that one of the principal suppliers of steel in Sheffield will give you the same service. In any case one of the oldest producers of steel in this country, the firm for crucible steel, now sell steel, according to their catalogue, as "deep hardening, medium hardening, and shallow hardening." I think that is a wonderful example of British progress and conservatism! That is how they label it, and all carbon contents, analyses and sections are obtainable. I should be quite happy to mention the name of that firm privately afterwards. I have not any shares in the firm, unfortunately. If there are any representatives of steel companies present who could give us any further information, with the Chairman's permission, we should be glad to have them.

Regarding the hardening of .020 in. springs on cadmium-plating, you naturally find they are brittle. It is an old trouble. We assume it is due to hydrogen effects from the plating.

May I ask Mr. Cook if he has tried a very low temperature annealing, say immersing in boiling water? (Mr. Cook: No). I have not tried that; I am speaking purely from theoretical knowledge. What you will have to avoid in avoiding brittleness is

losing the springiness of the material. You can certainly remove that brittleness by annealing at a reasonably high temperature, but it will remove the springiness which you require, and you might find that a boiling water immersion would avoid this. Failing that, I would suggest to Mr. Cook that he gets into touch with metal spraying. Some wonderful things are done in metal spraying, by producing an excessively thin corrosion-resisting coat on small sections.

Referring to the question of nicking for correct hardening, the appearance of the fracture is, of course, a very sound guide. It is a definite guide to the microstructure and probably serves quite as well as long as it satisfies you. Whether it is the best practice on magnet steels, I am doubtful because magnet steels depend so much for their qualities on subsequent ageing treatment. They are extremely sensitive to heat treatment and ageing treatment, and I very much doubt whether the nicking test on magnet steel is as good a guide as, say, the nicking test on ordinary hardened steel would be, I should be very doubtful about trusting only to the nicking test in magnet steels.

MR. COOK : I have found that in connection with diaphragms for horns, the life of the diaphragm is very considerably increased by a treatment of the kind Mr. Jones referred to, immersion in boiling water or hot molten salts. The life is increased about 10 times, a most surprising result.

Referring to Mr. Jones' remarks on the question of magnet steels, and I take it that we are referring only to tungsten magnet steels, I might perhaps relate an experience which might throw a little light on that. I was once put on to the work of salving some tons of 4% tungsten magnet steel which had been hardened above what we termed the recalescent point. At any rate, the steel, from the magnetic point of view, was completely ruined. I found by reheating and quenching at the correct temperature much of the steel could be used and formed the opinion that where this treatment was unsuccessful the carbon content had been altered by overheating and that this carbon content had a much greater effect on the magnetic qualities than anything else. Can one heat the steel and not affect the carbon content ?

MR. WILLIAMS : With regard to the question raised about the effect of carbon content on heating, I think it is very unlikely that the carbon content would be greatly affected unless the steel were so overheated as to be actually burned, or, on the other hand, unless the steel were heated in the presence of some oxidising compound or reducing compound. It may have been heated, for instance, in a body such as ferric oxide which is used for making malleable iron castings for reducing the carbon content. On the other hand, if heated in the presence of carbon or reducing gases

such as carbon monoxide, the carbon content of the steel might be affected, but in answer to the query as a whole I should think it was very unlikely that the carbon content of the steel would be affected by heating.

MR. T. W. HOOD : I have gathered from the paper a lot of information about grain size control in steel. Mr. Jones is quite right when he says it is possible to order it as such from an English firm. It is quite possible if you are frank about the purpose for which you want to use it. It is one of the common troubles of the steelmaker that the consumer is rather reticent as to the ultimate destination of the steel. Another point which has been raised is cost. The cost is not very much ; it varies according to the quality of the steel and I think I am correct in saying, in the case of the steel made by the method shown in the film, that there is no extra charge. One other point is that in talking about grain size control you have mentioned solely American Steels. Actually there was a paper read to the Iron and Steel Institute at the meeting in Germany, by Dr. Swindon and Mr. Bolsover, in which they give results that do not quite agree with many things the Americans have found. I am not very conversant with this paper, but I should like to draw Mr. Jones, attention to it.

MR. JONES : I hope I have made it clear to you that these benefits will only be fully obtained when there is a partnership between the steelmaker and steel user.

With regard to the work of Dr. Swindon and Mr. Bolsover, I thought that I had mentioned the recent experiments in this country in my paper. If I did not, please blame the clock, not me. Full reference to their very useful and enterprising work has been made. Naturally, in pursuing this subject for your Institution, I have explored all the available sources, English and Continental, and I have been grateful to Dr. Swindon and Mr. Bolsover for information and correspondence.

MR. WADDELL : I would like Mr. Jones to explain how the grain size of this steel is determined, because I know a little about steel and I am inclined to think a good many members of this meeting will consider that it is the grain size of the material, after their treatment, that is, if, after hardening a piece of steel, they break it and find a coarse grain they will say it is due to the original grain size of the steel. I believe that, in getting at these standards of grain size, the steel has got to be treated in a particular manner and then etched and examined under the microscope in its original state. It would be advisable for Mr. Jones to explain the treatment.

MR. JONES : I avoided this detail in the talk in order to keep principles well to the fore. I take it you are not interested in the mechanism by which the grain size is controlled ?

MR. WADDELL : No.

MR. JONES: It is a very involved metallurgical problem in which we could give many explanations and they might all be wrong.

How, given a piece of steel, can one determine the grain size? That is laid down in the test of the standards supplied by the American Society of Testing Materials. Samples are carburised at 927°C. for eight hours. A microphotograph is then prepared at one hundred magnification. That procedure determines what I referred to as the inherent grain size of the material. If you have a piece of steel which is being very satisfactory (or unsatisfactory—you ought to be interested in it in either case) and want to know what the grain size is, you must follow that procedure of carburising at 927°C. for eight hours and then prepare a micro section, and make comparison with the standard pictures.

You will find various practical and theoretical objections to that method of determining inherent grain size, but the subject is very involved indeed and I do not propose to discuss it here. There may be better methods developed in the future for determining this particular property of grain size. It may not be the grain size which really gives these properties, but the grain size is a key to it, most decidedly.

I am sorry to be vague. It is a little bit complicated in theory but practically, with a little bit of experience, it is quite simple.

MR. WADDELL: I wanted Mr. Jones to distinguish between inherent grain size and grain size produced after wrong heat treatment. A customer may get a piece of steel, badly burn it so that it has a very coarse grain size, and he may confuse that grain size with inherent grain size.

MR. JONES: It would be very difficult to wrongly heat treat a fine grain size material. The steel which is made by the steelmaker is coarse grain size. The moment the critical temperature is exceeded, that moment you begin to lose properties due to large grain size, but in the case of fine grain size material, made and accepted as such by the steelmaker . . . we have got to go up to 1,000° before we begin to spoil the steel. In other words, you must go home to lunch and have forgotten about it in order to spoil the steel. Does that answer the question?

MR. WADDELL: Yes.

MR. WHITE: It gives me great pleasure to propose a vote of thanks to these two lecturers for the admirable lecture they have given us. Mr. Jones said that Joseph Chamberlain told us to think imperially, some one else told us to think independently, and now he asks us to think metallurgically. I think he put that altogether wrongly; he meant think in grain size! It has opened up an entirely new field for us to explore, and I am looking forwad to the day when we can buy Widia and specify the grain size so that it won't chip off. I have no doubt that day will come. Mr. Jones

did not make it quite clear as to what extent grain size is applicable, what range of steels it covers ; does it go right down to cheap steel and right up to the very best steel ? Apart from that, he has covered a very wide range, and we are very grateful to the lecturers for their interesting and informative lecture.

MR. L. P. WILEY : We have had a paper to-night which, I think, is of interest to everybody in this room. It is a huge subject, and I do not know how Mr. Jones has managed to leave certain parts out and nevertheless give us an excellent statement of the case. Of course, I think it will be new to the majority of us. It has been wonderfully well delivered, and has been one of the best papers we have had. I have very great pleasure in seconding this vote of thanks.

MR. WILLIAMS : I am very grateful indeed to the gentleman who proposed this vote of thanks and to the gentleman who seconded it, but I have perhaps to take the first one to task because he mentioned Wida. Now some of us may know that Widia is not steel at all, and as for its grain size, we cannot give any guarantee at all. It happens to be a synthetic carbide of some description, which is kept pretty secret by the people who make it. But, on the other hand, cheap steel is, in one respect, exactly the same as the most expensive steel in that it has grains. All steels have grains. We are excluding, of course, Widia. It is perfectly right and proper that the grain size in a cheap steel should be controlled as well as the grain size in the very expensive type. The method of controlling it which was mentioned to-night by a controlled steel making practice and the addition of aluminium would, I think, present no difficulties to the steelmakers, and I think that if everybody in this room specified a particular grain size, the steelmaker would soon wake up to the fact that it was desired and make the necessary arrangements to meet the demand. I thank you for your very generous vote of thanks.

MR. JONES : I should like to associate myself with the thanks Mr. Williams has expressed for the very kind way in which you have received the paper. It is a tremendous satisfaction to Mr. Bond Williams and myself with our academical interests to be passing on to the industrialist that scientific data which may improve his lot very considerably, and make a better and more comfortable world for everybody.

HARDNESS, MACHINABILITY, AND RESISTANCE TO ABRASION.

Paper presented to the Institution, London Section, by Dr. Georg Schlesinger.

HARDNESS is the resistance to impression—the resistance which one body opposes to penetration by another. Machinability of a material is its conduct whilst being cut, using a certain shape of cutting-tool. As machinability depends on the resistance which the cutting edge of the tool finds in penetrating into the material, there seems to be no doubt that hardness and machinability must have some connection which has to be found for each case separately. Resistance to wear is the resistance of a body to the rubbing away or abrasion of molecules of material from its surface, when it works together with another body of the same or other material and qualities.

Abrasion between rolling and sliding bodies takes place if the vertical pressure between the working surfaces is increased to such a degree that the material of the surfaces is taken off because the small projections of the surface cannot take up the pressure, elastically. Abrasion is therefore splitting off crystals under the effect of pressure and friction.

Hard bodies often resist abrasion to a very marked extent and are difficult to machine, yet hardness is no reliable measure for resistance to wear. Bodies resistant to abrasion need not, on the other hand, be very hard and may therefore be easily machined. For example, soft sandstone grinds the hardened tool, while soft steel will wear a hard emery wheel. To prove this, the following test has been made with the intention to burst the wheel, if possible, even by a very high stress. These were the working conditions :—

(1) The circum.erential speed of the wheel V = 35 m/sec. (105 feet/sec.).

(2) The work-piece was of tenacious soft steel 40 to 45 kg./mm. 2 and ran with V = 38 m./min. (90 ft./min.).

(3) The cross-feed was hand operated with a course feed of about 0.4 mm. (0.015 in.), in order to destroy either the wheel or to burn through the safety-fuse of the motor (ca. 30PS).

(4) The longitudinal feed was 50 mm./rev., or 2.13 m./min. (70 in.) equal to the breadth of the wheel. In about three minutes there were ground off 100 mm. (about 4 in.) from the diameter of

the wheel, originally 488 mm. (19.2 in.). The wheel of 386 mm. (15.2 in.) was nicely round with 0.05 mm. (0.002 in.) eccentricity. The quantity of emery taken off was 3,500 cm.^{3} (244 cub. ins.) = 8.5 kg. (18.5 lb.). The quantity of iron ground off was 305 cm.^{3} = (18.6 cub. ins.) or 2.4 kg. (5.3 lb.) about one-quarter of the weight of the abrased emery. The great hardness of the wheel did not prevent its enormous wear, because the forces of abrasion worked across to the bond and crumbled it away. Thus, all depends on the conditions of work which must be known in each case separately.

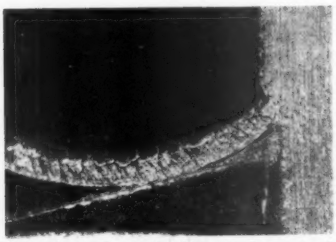
Which is the starting point for the explanation of the connections between hardness, machinability, and resistance to wear? Who makes the fundamental demands? The physicist (hardness), the production engineer (machinability), the user (resistance to wear)? As always, the user decides. He wants to buy a machine or a tool which will last a long time without much wear. At the same time the object is to be as cheap as possible, therefore it must be easily machinable. To be able to fulfil all these conditions, the material must be sufficiently soft, and, in any case, easily machinable. consequently, the question of abrasion is the very first of all considerations. The technological and economic demands are influencing each other very much, for it seems that abrasion, hardness, and machinability are just the three qualities of the bodies, the right choice of which is of decisive importance for the production shop. The material is determined neither by the physicist, the production engineer, nor the buyer, but only by the designer. The old saying that "manufacturing begins on the designing table," gets here its strongest and most evident confirmation.

The designer will always endeavour to create a body which maintains its shape a long time, while being exposed to the highest stress, without deformation arising by tension, compression, bending, torsion, or collapse. The body, while kept in permanent use without suffering any deformation, must not undergo any change of the geometric shape (flat surface, cylinder, cone, ball) by rubbing off molecules in consequence of wear (abrasion).

The choice of the right material as to : (*a*) resistance to forces ; (*b*) resistance to wear, is one of the most important tasks of the designer.

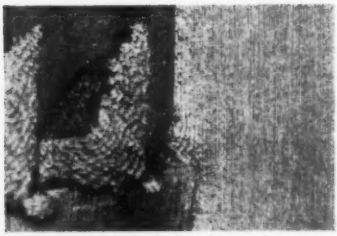
He makes the main spindle of a lathe of steel, because it will be bent, pressed, pulled or distorted and must be resistant in every respect. He has its bearing surfaces case-hardened and ground in order that it may keep its cylindrical or conical shape for a long period without wear. The spindle bearing is made of best bronze, the inferior resistance of which is compensated for by the stiffness of the housing, and because its qualities against wear are very favourable. If the main-bearing of the machine tool is well made, the whole machine will furnish good work.

Typical examples of the fact that hardness and resistance to wear are the decisive factors for different designs are the piston of light metal in the cast iron automobile cylinder, hardened gears meshing with each other, and hardened steel balls or rollers in the hardened races of roller bearings. The production engineer has to execute what the designer dictates and he will do so as long as the growing difficulties of machinability do not mitigate against output.

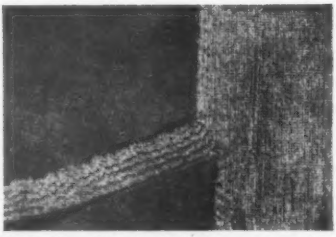


Formation of steel chip at low speed (75 ft. per minute).

Formation of steel chip at high speed (355 ft. per minute; other conditions identical).



Formation of soft steel chip produced by tool having incorrect angle (tool angle 80°).



Formation of soft steel chip produced by tool having correct angle (tool angle 65°; other conditions identical).

Fig. 1.

The Characteristic Features of Steel.

If the objects are hardened and then, for a high finish, afterwards ground, the machining of the hardened piece is possible without difficulty, but this does not apply with roughing and finishing or unhardened pieces which are to undergo, later on, certain conditions of work which always cause wear.

Considering now the admissible abrasion in connection with the hardness of the material, and with its resistance in general, the importance of the question of abrasion for the production engineer is proved by the simple observation of: (*a*) Cutting tools which are worn out by machining; (*b*) Machine tools which become inaccurate and make useful manufacturing impossible after a short life.

The cutting speed depends on the endurance of the tools continually wearing by abrasion. That is the measure, the pacemaker, of the whole workshop. Output is always dependent on the influence of hard and soft construction materials on the wear of the tools. Concerning materials, it is somewhat easy to characterise machinability by stating tensile strength, yield point, elongation, construction, notching-resistance, etc.

There does not exist at present sufficient data to fix an exact measurement for the use of tool-steels by physical or chemical quali-

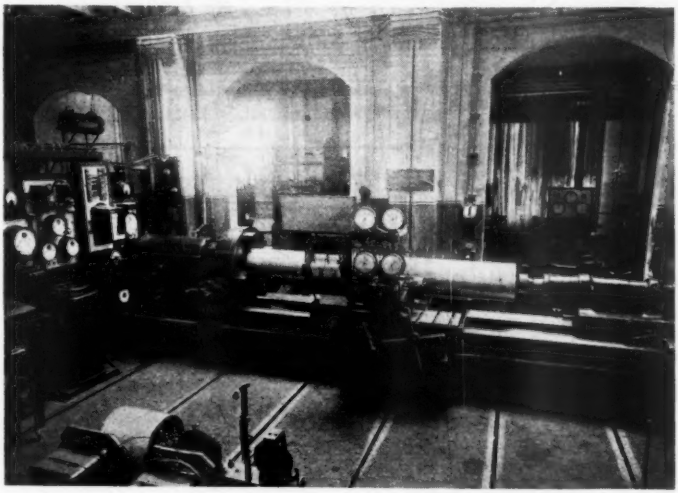


Fig. 2.

ties. The stress attacks first the sharp edge as hard as glass and rises to strains of increasing amount. The strain of the section in kg/mm.^{2} cannot be fixed and data concerning the resistance to pressure is not available. In addition, the effect of temperature rise at the working face makes it still more difficult to get a clear knowledge of the strain and its influence on the tool. Thus it is difficult to ascertain how a tool will stand up in practical use, because the physical as well as the metalographic research are not univocal.

The destruction of the cutting edge of a tool is the result of :—

(*a*) wear by mechanical rubbing ; and

(*b*) softening by influence of heating.

In most cases the cutting edge becomes useless by mere abrasion.

Great hardness is required for lathe and planer-tools as well as for drills, but is not so necessary for milling-cutters, which must not be so hard as turning-tools, for they seldom get soft by drawing the temper. The flowing-off chip wears out the face of the tool by

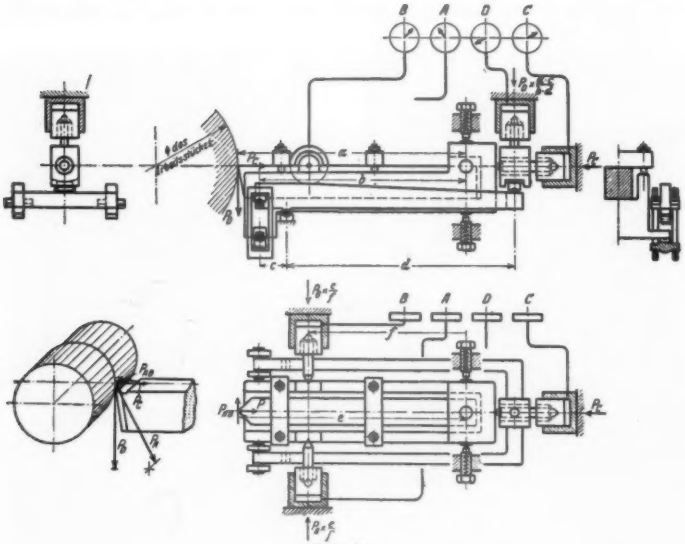


Fig. 2a.

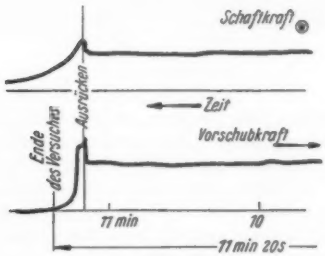


Fig. 3.

friction, the abrasion producing erosion, the depth of which depends on the hardness of the machined material. The resistance to cutting is measured indirectly by the abrasion of the tool :—

(*a*) By measuring the forces which result from cutting which

allows at the same time the facility to determine the life of tools up to the point of getting dull.

(*b*) By weighing the quantity of chips produced by rough cutting during a certain time, usually in one hour.

Fixing the section of chip as to depth and feed, say 4 × 1 mm. (0.25 × 0.04 in.) the quantity of chips depends only on the cutting

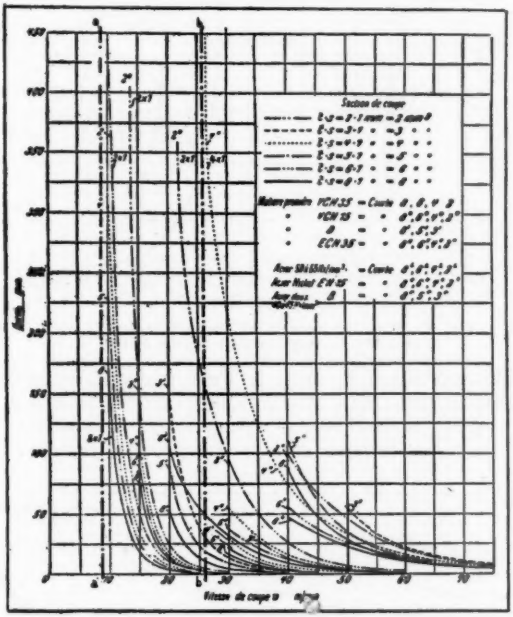


Fig. 4.—Chart for Chrome Nickel and Ordinary steels; *aa* and *bb* are tangents to the hyperbola.

speed. The shape of the cutting edge of the tool depends upon the material to be machined, and means must be provided to indicate when the tool becomes dull.

The main force in lathe cutting is measured by three components. Of these the shank-force and the feed-force tell exactly the moment of destruction by abrasion. The three cutting forces increase with the tensile strength and tenacity, as well as with the hardness of material. The kind of material, section of chips and cutting speed determine the life of the tool. The connection between them results from the T-v curves, for turning and drilling.

Taylor established the life-time to twenty minutes, V 20; Refa established the life-time to sixty minutes, V 60.

The author chooses 400 to I week; V 400 to V week. If there

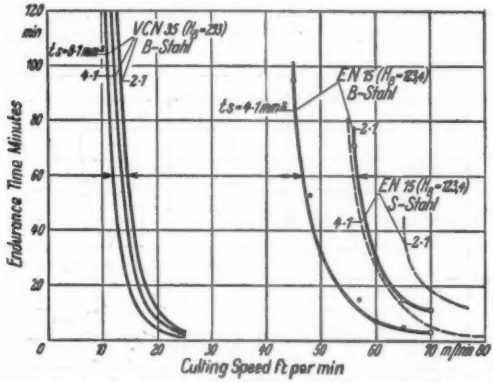


Fig. 5.—Tool life curves for turning steels VCN 35 and EN 15, with various depths of cut.

is any additional demand such as (1) quality of surface, (2) accuracy as to tolerance, then only the endurance of the tool and not its cutting capacity is decisive, for a very small wear of the cutting edge can spoil the finished surface and produce inaccurate work.

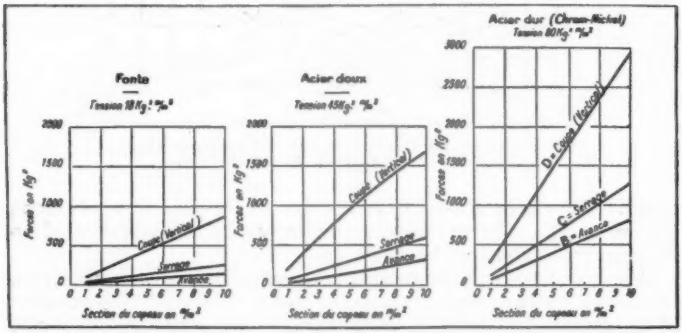


Fig. 6.—The Three Component Forces for Cast Iron, Mild Steel, Hard Steel.

An example may be furnished by an automatic screw machine on which 4,000 pieces were well finished in eight hours with 0.02 mm. with the same tool before it became dull. For such work a fine feed

is required, which means very small force and a speed only so high (inferior to V 60) that the cutting edge remains undamaged the whole working time.

In a similar manner as in turning, while drilling one can measure the feeding thrust as well as the turning moment with a dynamo-

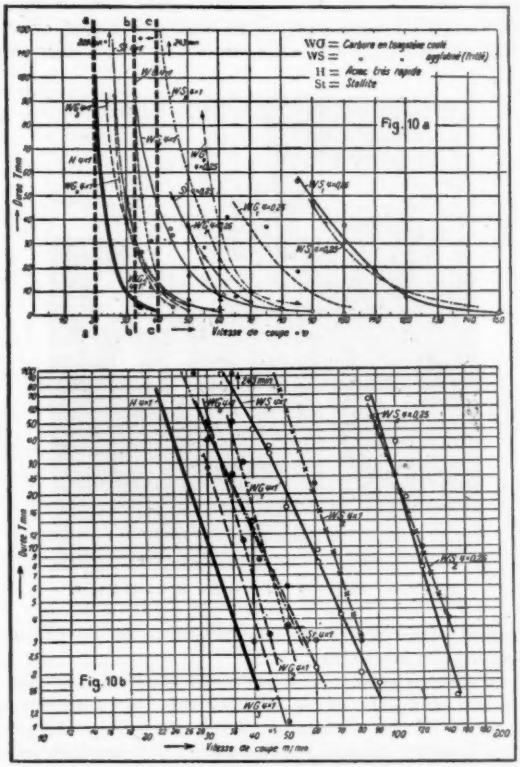

WC = Carbure en tungstène coulé
WS = " " "
H = Acier très rapide
St = Stellite
Fig. 10 a
Fig. 10 b
Durée T mn
Vitesse de coupe = v
Vitesse de coupe m/mn

Fig. 7.—Tool Life with various cutting speeds. High Speed Steel, Tungsten Carbide, Stellite, etc.

meter and draw the destroying cutting speeds, as a function of the depth of the hole. The characteristic feature of the test when completed is again the blunting of the edges which cannot be observed because they are hidden in the hole. The increase of the forces shown by the dynamometer shows exactly the point of abrasion

of the edges. Instruments for rapid testing are the pendelum-tests, Herbert and Leyonsetter, and the measuring of the rise of temperature at the cutting edge by Gottwein-Rechel. Of real importance only are the tests of endurance, the results of which can be transferred directly to the practice of the shop and these are exclusively used.

The execution of such tests of durability lasts comparatively long, demands first rate equipment and a number of very well trained helpers, working with care, especially on matters concerning

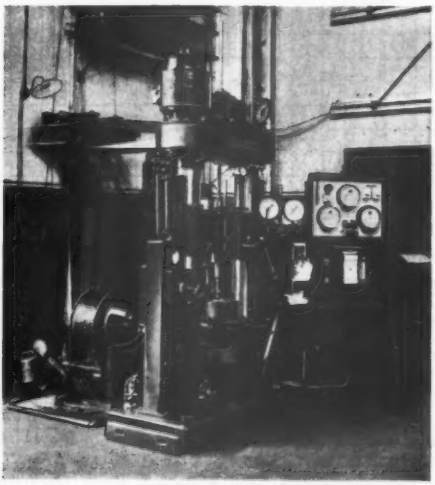


Fig. 8.—Drill Press with Gauge Dynamometer.

the treatment of tools. These men ought to be on the staff of a specially equipped laboratory.

Thus we have found in addition to determining the dulling of the cutting edge, the endurance for the machinability of steel. The endurance of the tool must be considered in the rate-fixing department to settle correct cutting speed. The production engineer can only work with this cutting speed directly, if the machine-tool has an indicator for the cutting speed, or indirectly when the number of revolutions " n " is calculated from $n = \frac{A}{\pi d}$ given to the workman.

It must be said that this is only to be taken literally for the standard quality kinds of steel, for the cutting edge can be worn by other influence than by the cutting forces. Carbide crystals in soft steel

cause considerable abrasion, while a material such as copper dulls the tool with a small cutting-force. Even for copper the rule is valid, the smaller the cutting-force the better the shape of the tool, for an increase of force=end of tool by inadmissable abrasion.

The economic time differs greatly from that determined by the wearing out of the cutter. The economical life is the working time of a given tool at the smallest cost for the manufacturing of a certain number of pieces. These expenses are composed of:

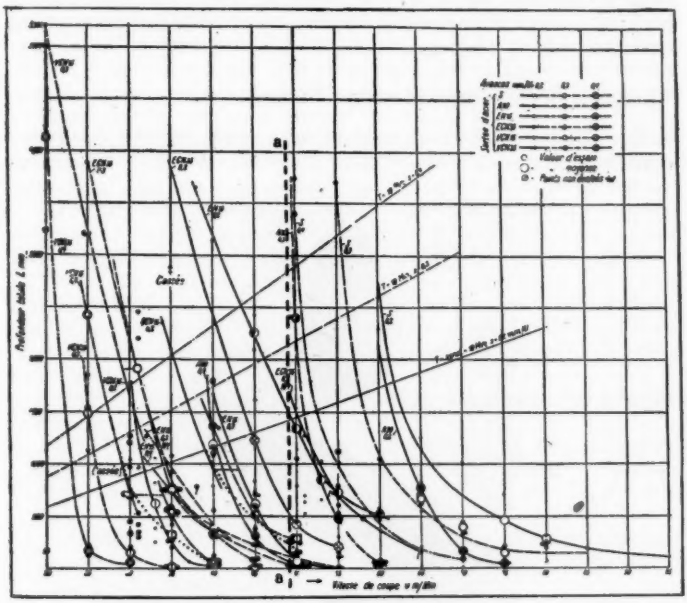


Fig 13 — Courbes de durée pour le perçage a, a = tangente caractéristique pour l'acier A 90.0,3

Fig. 9.—Drill Life Curves for High Speed Drills measured in penetration.

(1) expense for making the tool; (2) time for setting up the tool; (3) power consumption; (4) depreciation of the machine; (5) wages for doing the work of items (1) and (2), etc.

The total of these expenses will differ according to the management of the shop, the equipment of machines, shape of tools, tool-making department, etc. There are very complicated economical questions which should be considered in addition to the machining items. Often the time of one hour, V60, is taken as the economic time of endurance on the Continent. Then the cutting speed is chosen to

ensure that the tool becomes dull in sixty minutes. The conditions being similar in other respects, it is again the durability of the tool which decides material, hardness and cutting angles. Two of these three conditions, material and angles, may be kept unaltered. The hardness, however, depends partly on the skill used in hardening as well as on the material of the tool.

It is therefore difficult to make good, clear comparable tests. Even the repeated sharpening of the tool and its tempering to the same hardness is very difficult. Problems arise such as how much must be ground from the tool to take off the softened parts of the cutting caused by dulling.

Abrasion of Working Machine Parts.

The abrasion of the tool must be very small indeed for finishing operations, the slightest abrasion blunting the edge to change

Fig. 10.—Wear Protection by use of Widia.

a sharp cutter into a dull one and require regrinding. When the right shape is again obtained, the clamping devices will allow for adjustment of the reground tool in the correct position to the work piece, so that the abrasion is compensated. Even in normal roughing,

the admissable blunting never means real destruction of the cutting edges.

Of quite a different effect is the wear when two machine parts work together. This always causes, after a certain time, such a remarkable change in the shape of one of the bodies, or both, that they must be dismantled and one or both replaced. Sometimes a certain adjustability for the wear has been provided, so that in spite of the changed shape, an admissible compensation is possible for a longer space of time. Piston rings are elastic, valves can slide deeper into their seats, carriages and tables have adjustable gibs for wear, bushings of bearings can be compressed, etc. In some rare cases, to prevent wear, brazing or welding a resisting piece such as Widia on the basic soft metal is employed. The compensating design depends on the fact whether rolling or sliding friction, or combinations of both, take part of the abrasion.

The abrasion between the working surfaces depends on : greater or smaller pressure, speed of motion, hardness and quality of the surface of the wearing means, regular or shock attack, regular temperature or increasing by abrasion. Wear is generally measured by the abrasion of material itself which is weighed or calculated from the worn volume of metal. The machines for testing abrasions differ, on the one hand, by the kind of friction produced, rolling or sliding friction, or on the other hand, by the way the working bodies are pressed against each other. A short summary, giving at the same time the name of the designer, will illustrate the constructions in use known to the author :—

(1) Sliding friction (friction of bearing) with adjustable pressure, with or without greasing (Amsler).

(2) Sliding friction with adjustable pressure by a rotating thin steel disk, which causes a cutting-in or grinding-off effect of a small block is employed by Hanffstengel, Spindel M.A.N., Skoda-Sawin.

(3) Sliding friction with adjustable pressure using an abrasive material (Scheibe carborundum wheels, Robin emery cloth, Brinell pulverised quartz).

(4) Rolling friction with adjustable pressure and additional slip (Amsler, Nohr, and Federhaff, Spindel, Stanton, Saniter).

Corresponding to the way of testing and the testing machine, the results vary greatly. The testing method must be accommodated as near as possible to the practical conditions.

Some of the wear testing machines, which are typical and proved designs, although it is recognised of course that other successful machines are available, may be briefly described.

The Amsler machine allows wear tests by : (*a*) rolling friction ; (*b*) sliding friction ; and (*c*) partly sliding, partly rolling friction. Two discs of the metals to be tested are run under pressure (sizes

30 to 50 mm. $\times$ ϕ 10), with their circumferences one on the other. It is possible to regulate their relative speeds so that the upper disc which is pressed down, is either rolling, sliding, or both. It can also be stopped entirely and be replaced by a small block. The wear

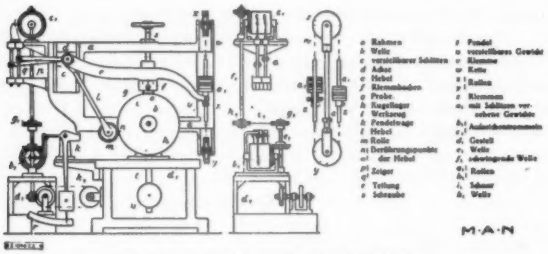


Abb. 3. Schema einer Abnützungsprüfmaschine Bauart Spindel.

Bauart.

Die Bauart der Maschine ist aus den Abbildungen 1–3 ersichtlich. Die eigentliche Prüfeinrichtung ist auf einen starken Rahmen aufgebaut, der auf einer Welle sitzt, die in der gleichen, geometrischen Achse mit dem zu prüfenden Werkzeug oder Werkstück auf einer drehbankähnlichen Antriebsvorrichtung drehbar gelagert wird. Der Rahmen trägt in einem

Fig. 11.—Wear Testing with interrupted load.

is determined by weighing the testing wheel before and after, and the deformation of the shape is altered by the rolling action by measuring the diameter before and after the trial.

With the Spindel M.A.N. Nürnberg machine, the metal is either sliding slowly on metal or is rolling with adjustable slip, while work

Maschine zu bauen, mit der sich auch wirklich brauchbare Ergebnisse erzielen lassen. Die Abbildung 3 zeigt die Prüfmaschine Bauart Spindel in allen ihren Einzelheiten.

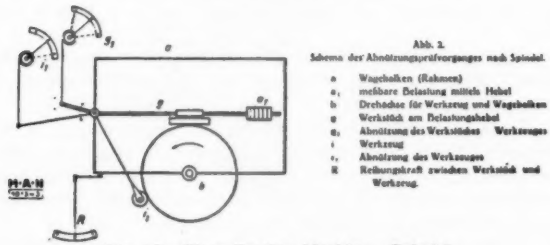


Abb. 2.
Schema der Abnützungsprüfvorgänge nach Spindel.

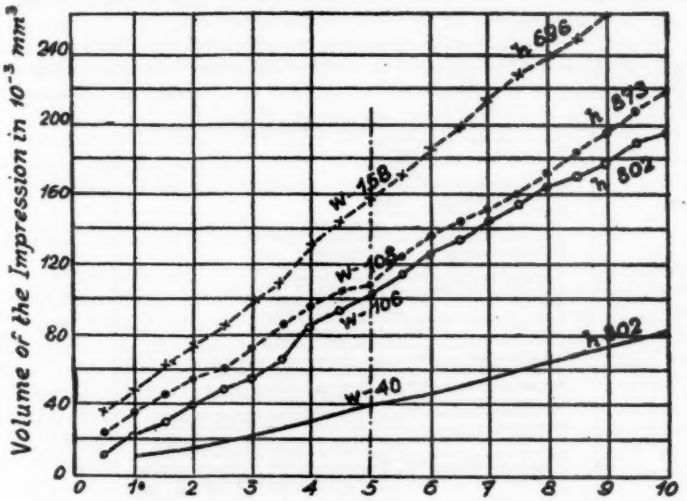
Fig. 12.—Wear Testing Machine. Spindel.

can be done with adjustable pressure, sliding speeds and temperatures, also with or without lubrication.

With the most used way of testing, a steel disc of 1 mm. thickness grinds a circular segment into the piece to be tested. The wear

of the piece and of the disc as well as the power of friction, are automatically registered. The time is measured as abscissa, in which the rotating disc has ground with its mantle-face a segment of certain depth into the original surface of the sample when the pressure and the circumferential speed are given.

Spindel has found in conjunction with practice that resistance to



Test No.	Symbol	Block Gage	Vickers Hardness 10 kg	Vickers Hardness 50 kg	Wear
1	×---	20mm. carbon tool steel	690	696	158
2	•---	20 " " " "	847	873	108
3	o——	17 " " " "	762	802	106
4	——	20mm. 18% tungsten steel	762	802	40

Fig. 13.—Wear Test Curves of four steels.

abrasion has much more relation to machinability than to the hardness and ductility, because wear is based on the high structure. If the depth of wear with dry metals is not sufficiently deep, to about 1 mm., in no case below 0.2 mm., the finish of the surface is tested and not the resistance to abrasion.

The wear-testing machine after Skoda-Sawin is similar to the appara-

tus of Brinell-Rockwell-Vickers, as to the arrangement and the application. The fundamental idea is also that of stationary blocks to be tested by a rotating disc, which is made of "Widia" and therefore practically insusceptible to wear. The resistance to wear is determined by measuring the contents of the notch in 0.001 mm.^{3}, which is measured with a certain number of revolutions and a certain weight. The minute impression does not spoil the surface and can be made directly on the piece in the shop.

The test piece is cooled, the coolant taking off the chips and a microscope is used to measure the impression while an auxiliary data sheet facilitates the calculation into 0.0001 mm.^{3} Soft and hardened

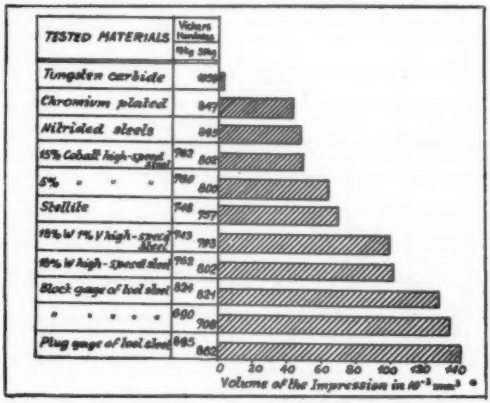


Fig. 14.—Hardness and Wear of various materials.

surfaces may be tested. The numbers of revolutions are fixed at 3000 ± 6% with a speed of 675 rev./min. for the "Widia" disc, this having a size of 30 mm. $\phi \times 2.5$ mm. thickness. The test lasts about fifteen minutes.

The classification of the wear, both after Skoda-Sawin and after the Vickers hardness is shown. Two pieces of equally high hardness: H=802, have quite different wear Nos. 40 towards 106. A testing method is only useful if the tests furnish uniform results and can be repeated without difficulty.

Conclusions.

It was found that there is no univocal relation between the wear of steel, and the quantity of pressure, to the speed of motion and with rolling or sliding friction without grinding means to the hardness of

the attacking body. A smooth surface diminishes abrasion, a rising of temperature increases it. Further, there is no univocal relation between the quantity of abrasion, that is to say the resistance to wear, and the other physical qualities, as well as the chemical composition of steel.

The hardness of the kind of steel submitted to abrasion is however of great importance, as well as the possibility of cold-hardening caused by the forces which produce wear (hard-braking rail wheel tyres). Of great influence is the tenacity of the steel and of the parts which were cold-hardened by the movements of wear. This tenacity depends on whether the exterior surfaces of the working parts scale very much or not. Different kinds of wear depend on the different qualities of steel. Therefore the same material may stand one stress well and another stress badly. This refers in a similar way to the different test-methods.

The Influence of Hardness.

In making tests of durability, what is characteristic of the quality of the tool and the kind of metal? It will be understood that both these questions must find a clear answer, for otherwise it is not possible to transfer the tests of endurance from the laboratory to the practical workshop. Supposing that the angles of the tool are standardised and are used everywhere in the same way, the shape of the cutting edge is known and is not of importance at the moment. Cutting tools must be very hard, for a tool which is not hard enough will wear quickly. This settles the relation between wear and hardness of tools. Further there is the question of hardened steel, self-hardening or sintered metals (tungsten-carbides). These surfaces resist energetically to the penetration of hardened bodies and it is only possible to scratch the surface (Rockwell, Vickers, Turner), with a body of still greater hardness, practically without wear (i.e., diamond, the Brinell steel ball is much too soft), so the hardness must be determined by the rebound of a falling body (Shore's Scleroscope)

With H.S. hardened steel there is often a thin soft layer on the newly hardened surface, which must be ground off before testing the hardness. There are very few shops which decide the hardness of a tool with the help of a measuring instrument, when they harden a tool or regrind the blunt edge. The tool maker regrinds the tool for a second or third time, or he anneals, hardens, and grinds it again simply according to his own personal judgment.

Tools made of stellite, widia, wimet, carboloy, etc., being sintered, possess great hardness all through. Therefore they may only require regrinding and will not be exposed to the, in many cases, unskilled treatment by fire of more or less experienced toolmakers.

Kind of furnace	Place for hardening	Kind of steel	Section of tool shank	Hard'd No.	Gnd. No.	Time of endurance min.	Remark
Gas furnace.	Furnishing steel work.	A	Solid (1½ in. × 1 in.)	I	1	7.3	Considerable increase of durability after each regrinding.
					2	5.0	
					3	5.5	
				II	1	6.6	
					2	4.5	
					3	4.0	
				III	1	8.5	Increase after most careful hardening.
					2	5.0	
					3	7.0	
Electric salt bath. 1250-1350	Research lab.	A as above.	Solid (1½ in. × 1 in.)	I	1	7.5	Great decrease.
					2	4.2	
					3	3.8	
				II	1	9.8	Great increase oscillating conditions.
					2	4.1	
					3	9.6	
				III	1	11.4	Very high increase, very constant, careful hardening.
					2	12.5	
					3	11.2	
Electric salt bath. 1250-1350	Research lab.	B solid	(1½ in. × 1½ in.)	I	1	17.0	Very high beginning with right hardening.
					2	15.2	
					3	6.5	
				II	1	11.6	General decrease from I-III.
					2	15.8	
					3	6.5	
				III	1	12.0	Very great oscillation after each regrinding.
					2	9.4	
					3	3.3	
Charcoal furnace.	Research lab.	Solid	(1½ in. × 1½ in.)	I	1	17.3	On the top very great hardness.
					2	17.3	
					3	4.0	
				II	1	19.8	A great decrease with all three tests.
					2	16.0	
					3	10.0	
				III	1	16.4	Finally failure.
					2	2.0	
					3	3.9	

TABLE 1.

Table 1 represents a laboratory test carefully carried out, in which two tools of different hardness, marked A and B, were hardened in separate furnaces, by different tool-makers, each three times and reground three times, $3 \times 3 = 9$ cutting trials. Cutting speed and section of chip were kept constant in all cases, and the specimen of steel was the same from the first to the last test. The results of durability differed greatly, depending on the place, furnace, and carefulness. There was no explanation to be found as the hardening was done in the laboratory in furnaces installed for the purpose by a skilled hardener with double control of tem-

perature (Thermoelement-Wanner pyrometer). The tests with the scleroscope after regrinding showed deviations to ±30%.

What has been said for the tool applies to the metal to be cut. It is necessary to know its hardness, otherwise it is impossible to give a right cutting speed. The Brinell test is the simplest and most sure way to measure the hardness of unhardened steel. The impression can usually be made on a part of the surface where it does not affect the appearance. In testing the durability, every layer of the metal must be impressed before completion, for according to experience, the metal of a thick piece (16 in.=400 mm ϕ.) has a decreasing hardness to the centre (6 in.=150 mm.) often up to 10 to 15% of the original Brinell hardness of the skin. If the changeable Brinell hardness is not checked carefully, long and expensive series of tests may be useless.

Testing the hardness of the kind of steel to be machined is of high importance because its knowledge gives information as to the machinability. The resistance to wear never depends on the ductility or hardness of one material alone, but always of both materials influencing one another and on the conditions of work. Fifteen years ago the testing of hardness of material was limited to material softer than a hardened ball of steel (Brinell). By the introduction of the diamond cone (Rockwell) or the diamond pyramid (Vickers) as penetrating bodies, all the fields of hardened and self-hardened materials became accessible to the hardness test.

Brinell hardness testing consists in the pressure of a steel ball, diameter D being impressed with the static working force P=3,000 Kg. or 500 Kg. into the material for thirty seconds. The Brinell hardness is calculated as the force of pressure referred to 1 mm² of the impression surface to

$$H=\frac{2P}{\pi D\,(D-\sqrt{D^2-d^2})}$$ wherein d is

the diameter of the impression given in mm. The Brinell test is the most commonly used, but the application is limited to unhardened and not too hard metals and has the disadvantage that the measurement of the diameter of the impression requires the use of a microscope.

Vickers hardness test consists in the use of a diamond pyramid of 136°, as the impressing body. The value of hardness is found by a microscopic measurement of the diagonal (D) of the quadratic impression. It is remarkable that the Vickers number with soft material is nearly the same as that of Brinell. The preference for Vickers hardness test is that the variations of the ball impressions of the Brinell test are avoided, (caused by the degree of deform-

ability of the material), as only concave or convex bendings of the quadratic sides take place, while the corner distance D which is used as measurement of hardness does not change. The disadvantage of this hardness test is that the very small impressions can only be checked with the help of a special microscope and the calculation of the numbers of hardness are dependent on the magnification.

The Rockwell method uses a diamond bevel to impress the body and obtains the value of hardness by measuring the depth of penetration. The advantage of this way of testing consists in the values of hardness being read at once on a dial. The disadvantage of this test is that in consequence of the small impressions with soft

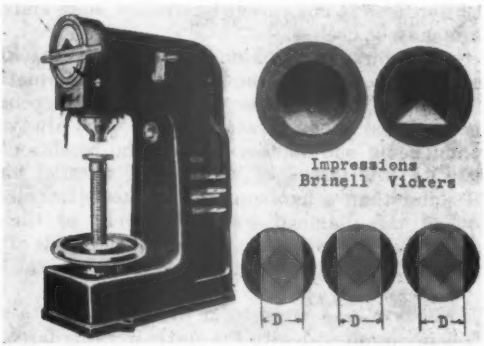


Fig. 15.—Dia-Testor (Poldihutte) 500 Tests/hour.
Diagonal D = Value of Hardness.

material a constant number of hardness cannot be found. The demands of practice often require a machine by which both hard and soft materials can be tested, by using one scale of hardness.

These considerations led to the development of the *Dia-Testor Machine* (Hessemüller & Wolpert, Ludwigshaven/Rh.). The fundamental principle of this machine consists in the combination of the Brinell as well as the Vickers test in one single machine and therefore the trials from soft up to the hardest materials are possible. Corresponding to the kinds of testing, the hardness numbers are determined by the valuation of the surface of impression.

The great advantage of this testing machine consists in that it is not necessary to make microscopic measurements of the imprints. The impressions are projected on a matted glass and it is not necessary to take the test piece out of the machine. The size of the impression can be read at once with the help of a scale fixed on the matted glass. The simple way of handling the Dia-Tester allows about 500 tests in an hour to be taken.

If the result of durability tests for different kinds of steel are not obtained from the time of endurance T and cutting speed v but after v and the Brinell hardness H, it will be found with fair accuracy that the machinability diminished with increasing Brinell hardness. The hardness of the tested steels rose from H=120 to H=295 and the cutting speed decreased from v60=58m/min. (175ft. to v60=15m/min. (45ft.). This curve is based on values easily determined in the shop. (1) E with the Brinell press, or (2) with the speedometer on the moving piece while turning or on the rotating tool as in drilling.

Keeps-Lorenz drilling test. This was originally intended to be used for hardness testing in general, but while it did not prove to be suitable for steel, it is of value in testing the hardness of castings.

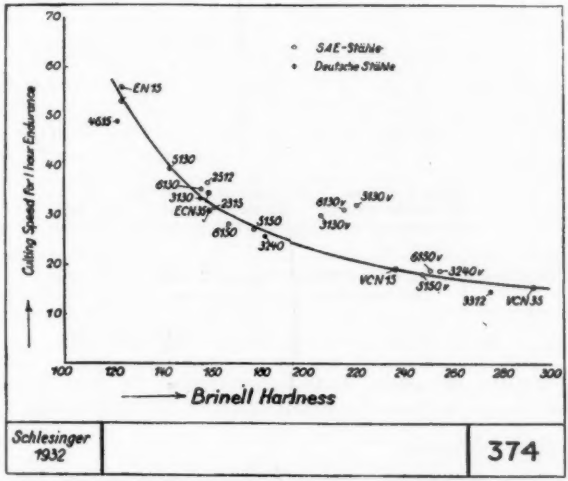


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Fig. 16.—Relation between Machinability and Brinell Hardness.

An indispensable condition of work with this test in addition to Brinell hardness and the cutting speed, is that the drilled hole must be kept free from chips. This deep holes in hard steel (H=250) can be drilled with less danger of breaking the drill than soft but tough material (H=120) which sticks so that fine chips build up on the edge and the drill breaks because the edges are cold welded with chips so that they are unable to cut.

The drill test is really a measure of usefulness of the drill for it cannot well be used for testing the hardness of the material unless different shapes of flutes, points, and cutting angles are provided

for each material of varying hardness and toughness. In consequence, it is not possible to compare the tests based solely on constant cutting angles.

The turning test to the destruction of the cutting edge without limit of time will remain, as it seems the most reliable. It is immaterial with these tests whether hydraulic or electric measuring

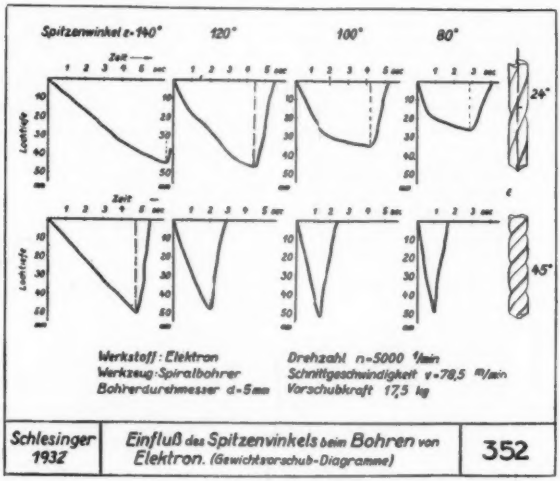

Fig. 17.—Influence of Point Angle in Drilling Elektron.

dynamometers are used ; the only requirement is that they indicate sufficiently quick about $^1/_{20}$ second and with little deviation ± 5%.

Structure Influence.

The high content of pearlite in steel causes natural hardness. With pearlite steels the resistance to abrasion increases with the size of grain. This leads to the importance of the structure of the steel in reference to wear in general. The science of structure is a field of which the author has no thorough knowledge, and on which he cannot report from personal experience. Therefore we will only consider the most necessary details, just as much as the production engineer must know to be able to follow the discussion. A very important part of the science of structure is the metallography which opens the structure by an enormous magnification of the polished and etched surface of the specimen and then makes a microphoto with the strongest light possible.

Nevertheless, we must understand the professional phraseology as: ferrite, pearlite, cementite, martensite, austenite, etc., and have some knowledge of their meaning. Anyone wishing to go further in his studies, must try to get acquainted with the curves about heating and cooling and, above all, with the immensely important iron-carbon diagram telling him all particulars. Every production engineer ought to try to understand these.

The kinds of steel which are machined in the shop are determined by the designer as to their resistance to wear which corresponds best to the purpose of application. The production engineer takes interest in their hardness and machinability, which are, as proved, not the same, and this feature refers not only to the ordinary kinds of steel, but to refined steels, such as chromium steel, manganese steel, nickel steel and nitralloy steels.

The Behaviour of Cast Iron.

From the standpoint of machinability, cast iron is much simpler in comparison, than the many variations of steel, and its adaption has possiblities of use in soft, normalised, hardened and tempered forms. The cast iron piece arrives in the shop in a prepared form which is practically ready, and after having taken off the skin from the surfaces there will seldom be required any heat-treatment, artificial ageing, refining or hardening. Thus, the difficult conditions mentioned concerning steel do not exist. In most cases one intentionally avoids all heating, to prevent new strains which might disturb the state of rest of the cast piece.

It is therefore understandable why the research of cutting metals deals mostly with steel. Machineparts highly stressed by tension, bending, buckling or torsion, arenearly always made of steel and machined all over. On the other hand, cast iron parts are generally subjected to compressive stresseswhich they are able to stand about equally as well as steel. For torsional and bending stresses also, it is in general possible to make the strained sections sufficiently strong in steel. Think of the development of highly stressed gears. Cast iron has been superseded in spite of good running qualities, by steel gears possessing great hardness, good oil retaining and long life. Cast iron is replaced in most cases by hardened and ground chrome nickel steel, which is much stronger and allows much smaller dimensions. The efforts of founcymen in the last twenty years have been mainly to create high quality cast iron, to increase its resistance against tension and bending, to decrease weight by diminishing the thickness of the wall, and above all to combine a sufficient hardness and resistance to abrasion with easy machinability. The principal advantage of cast iron pieces is that on account of the founding process, only a minimum of surfaces has to be machined. The

fabrication process by welding sheet steel is only useful for simple constructions.

The excellent qualities of cast iron slideways on beds of machine tools have not been replaced until recently by a few introductions of hardened and ground steel slides, the secure fastening of these on the bed casting leading to new difficulties.

Of all problems, that of the guidance of cylindrical and plain shapes has always been of high interest. Guideways must continuously keep their form, and wear should be as small as possible. If wear really occurs, the abrasion should distribute itself uniformly,

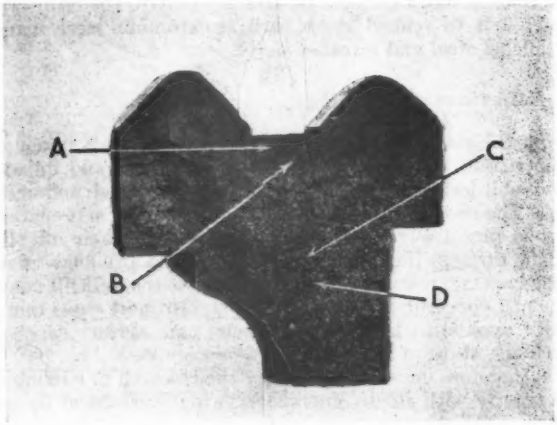

Fig. 18.—Varying hardness in section of a chilled casting.

(*a*) **Very hard and dense chilled iron.**
(*b*) **No porosity—chilling effect.**
(*c*) **Structure of soft cast-iron.**
(*d*) **Not the least effect of chilling.**

that is to say, wear should take place so that as far as possible the original geometric form will remain plane, or the cylinder will remain round. Therefore, the demands for cast iron are: (1) great resistance to abrasion. (2) uniform structure.

The composition of cast iron should be such that its resistance and hardness allows easy machining, and while hardness is of some influence, high Brinell hardness (H=220) can be combined with good machinability, while the resistance to abrasion does not increase with the Brinell hardness. In the years 1926-1935 quite a number of important wear tests were made. Typical examples of these tests

include : sliding surfaces, piston and cylinder, carriage or table on bed, shoe brake and wheel, and for rolling surfaces : gears, rolls, wheels on rails, etc.

If the dryness of the working surfaces is diminished or entirely ceases, abrasion gets less or is entirely prevented. This effect takes place on machine parts with lubrication which removes wear by full liquid friction or reduces it by half liquid friction.

To prevent wear in a main spindle bearing, the lubricating devices should be as good as possible to ensure an adequate supply of oil to reduce friction. With the usual prismatic guides of the lathe bed, half liquid friction is generally used, and in this case the dust of the shop is especially damaging, for the oil film is very thin.

Fig. 19.—Wear testing of various slide surface finishes.

With pistons and cylinders of internal combustion engines, the lubrication is introduced together with the liquid fuel between the working surfaces. If lubrication fails, abrasion results even up to the point of seizing, and ruin of the surfaces follows. The worn metal is torn from the original mass in small molecules of abrasion dust, and much depends on whether the dust arising between the surfaces in motion, is removed or not. In the latter case wear will increase in a multiplied proportion, but by a supply of lubricant and keeping the surfaces free from dust so that dust and lubricant do not mingle to form a grinding paste, wear is greatly reduced. There-

fore one can regard the resistance to abrasion of the guiding surfaces as a special quality of the material which, with uniform metal and uniform conditions of work, depends on : (1) sliding speed and specific pressure ; (2) absence of lubrication or rubbing means (dust) ; (3) possibility of corroding influences ; (4) quality of machined surface ; (5) temperature.

This multitude of factors which influences the amount of abrasion, proves that the appearance of wear which occurs in practice is very complicated, and it is almost impossible to imitate the complex conditions in a laboratory test. As a result, there remains no other alternative but to carry out the tests as near as possible to the actual case under consideration and to find, by comparison of the test results with the reality, reliable and useful co-efficients.

The author experimented with a lathe bed and saddle loaded

Zahlentafel 2
Ergebnisse von Zerreißversuchen, Biegeversuchen, Druckversuchen, Härteprüfungen [1])

Werkstoff	Zug-Festigkeit σ_B kg/mm²	Biege-Festigkeit σ'_B kg/mm²	Druck-Festigkeit σ_{dB} kg/mm²	Brinellhärte H 10/3000	Shore-härte	σ_B : H	Schlagfestigkeit a) (Kerbzähigkeit) mkg/cm²	Bearbeitbarkeit [4]
Temperguß .	29,0[3])	—	145,0	179	25—27	16,2[3])	—	—
Bauguß . . .	10,8	20,5	—	121	—	9	—	18,1
Grauguß B .	21,10	35,1	90,2	184	37	11,5	0,50	10,4
Grauguß C .	—	38,2	82,5	192	34	—	0,50	8,6
Spezialguß D .	19,3[3])	48,6	96,1	207	35—40	9,3[3])	0,51	7,1
Spezialguß E .	24,0	47,9	90,4	209	40	11,5	0,51	6,4
Lanz-Perlit .	29,2	49,9	99,1	212	38	13,7	0,86	5,9

[1]) Sämtliche Proben sind einem Biegestab entnommen.
[2]) Bruch zeigt Fehlstellen.
[3]) Unbearbeitete Rundstäbe rd. 30 mm ⌀: Stützweite 12 cm.

Fig. 20.—Table of results of Tension Bending, Compression and Hardness of Various Cast Irons.

with a weight corresponding to the maximum cutting force, and ran it day and night with good lubrication of the working surfaces until the running time corresponded to a working activity of three years.

At the same time a welding process to repair blow holes in cast iron was tried. Defective parts in the slides of the bed were filled in with molten cast iron by an acetylene burner, the results being excellent. The wear test was made in the following way : one part of the original guiding surface was taken out so that it represented the unworn surface to be used for comparison with the working surface. The measuring was done with a Zeiss Optimeter, allowing the accuracy of the tests to be exact to .I micron. The original state

of the ground slides has full lines in the diagram. The measurements up to 90,000 traverses have long dotted lines — — —, those after another 180,000 small dotted lines....., altogether 275,000 double traverses.

As the total deviation of the three lines is only 0.3 microns the abrasion was practically zero. This splendid result was caused by the entire absence of dust in the hall, good lubrication and the uniform hardness of the working slides and bed surfaces. In a similar manner Wallichs and Gregor tested automobile cylinders and piston rings as to their wearing qualities.

To get a diminution of the hardness, and at the same time an increase of resistance to wear with cast iron, two methods have been developed. (1) By improving the whole structure by the pearlite casting. (Sipp/Lanz). (2) By adding constituents to the chemical combination, especially nickel and chromium, and heat treatment. The effect has beeen examined by a great number of scientists, mostly practical engineers, and reference made as to : (a) hardness ; (b) influence of the constituents of the alloy ; (c) quality of the surface ; (d) structure ; (e) heat effect ; (f) thickness of the wall.

Considering the results of the researches : (a) *Hardness.* The absolute hardness in Brinell is only a relative measure for the resistance to wear of a cast iron test piece. The abrasion of high grade cast iron is determined by the difference of hardness among the moving and stationary casting. The wear is smallest when the difference of hardness equals zero. If the moving part is harder than the stationary one, the conditions are better than in the reverse case, that is, if the piston rings are softer than the cylinders, the cylinder will wear more than the rings and the abrasion will be greater than vice-versa. Wear diminishes with increasing hardness of both.

(b) *Influence of the constituents of the alloys.* The influence on wear corresponds to the influence of the special constituents on the hardness.

(c) *Quality of the machined surface.* Wear is a physical process in which some crystals are torn out of the surfaces of the moving parts and effect abrasion. Soft particles have the advantage of hardened ones in that they can deform themselves plastically, and that entire crystals are not torn out of the basic material. This necessitates special attention being paid to the quality of the surface.

High quality gray castings require very highly finished machined surfaces, while castings with a hardness of H=220 B.E. require a better quality of surface than those with less hardness (grinding, lapping, honing).

With cast iron, H=180, a plastic deformation is made by

running in and consequently, in a natural way, a surface as smooth as a mirror is produced.

(d) *Structure.* A pearlite basic mass of great hardness gives the best conditions of wear, but it is entirely dependent upon the formation of the right structure in the state of solidification. The state of structure of the finished casting must above all contain pearlite free of ferrite, excluding laminated ferrite. The co-efficients of resistance of pearlite increase enormously with the dynamic stress. The Lanz-pearlite brought the resistance to tension as the decisive feature and the bending test as the supplement.

Nowadays, instead of the middle cast iron of 14 kg./mm.^{2} resistance we have four classes: 14 — 18 — 22 — 26 kg./mm.^{2} and are able to increase the resistance. The Brinell hardness varies at the same time between H=180 and 220 (200 ± 10%). Both kinds resist abrasion well.

There is a relation betwwen machinability and abrasion still unexplained, which is very different from that of steel.

(e) *Constancy of texture in annealing.*—If the temperaturere remains under the pearlite point (700°C.) pearlite castings are of great resistance to the decay of structure in graphite and ferrite. Annealing makes the castings altogether softer. Phosphorous and nickel lose their influence on the hardness of the structure. Chromium works very much against the effect of fire.

In the practice of motor design, we have always high temperature (super-heated steam, gasoline, oil engines). According to Klingenstein the conditions of wear do not change up to 250°C. of temperature. The state of real annealing is seldom reached.

(f) *Influence of the thickness of the wall.* Thick walls of the castings of usual gray cast iron have generally less wear than thin wall-pieces cast from the same ladle. Thickness of wall and texture are always in close connection. The pearlite structure remains uniform with big walls and also if the sections are changing, in consequence the resistance to wear is unchanged.

Much disputed, and not until recently properly understood, is the question of the relation between the mechanical qualities of cast iron and its resistance to wear. Neither tensile strength, the Brinell hardness, the bending test, nor the drill test give an univocal measure. It seems, judging from the results cited, that the structure is of great importance, especially the increasing share of pearlite. But even this depends on other constituents of the cast iron. Perhaps systematic research on the machinability of cast iron, with further study of the quality in relation to resistance to wear, will settle the matter. At present no one really knows what kind of connection may exist between hardness and resistance to wear of cast iron.

The relations between hardness, abrasion, and machinability

are the basis of design and manufacturing. They influence the tool and the machine tools in the highest degree, for their research has formed the basis of the art of cutting metals.

The conditions are always changing, as the kinds of metal both for tools and work pieces are continually being improved. The results of this practical research are alike interesting and most important for the steel worker, the foundryman, the designer, the production engineer, and the use of metal implements. If I have succeeded in emphasising this important fact to my audience, the aims of the lecture have been attained.

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Discussion.

COLONEL L. SADLER (Section President, in the Chair): I feel sure that Dr. Schlesinger will appreciate your applause far more than any words I have to say, but I would just like to add my own personal pleasure, as I have thoroughly enjoyed what I term to be a technical paper expressed in a very practical manner.

DR. G. A. HANKINS: The Chairman introduced me as coming from the National Physical Laboratory, and I would like to say on behalf of the Laboratory that we appreciate the fact that you have asked a representative to come along to the meeting this evening. If we can assist production engineers we are pleased to do so. But I feel just a little diffident in speaking, because although I have endeavoured to keep in touch for some years with hardness and abrasion testing in general, I know comparatively little about machinability, and that I feel sure is a most important matter to all production engineers.

Dr. Schlesinger in his lecture has given considerable food for thought, and there are a number of points in which I am distinctly interested and should like to raise. In the first place I agree with Dr. Schlesinger that the combination of hardness, machinability, and abrasion is a most complicated subject, and a real difficulty about it is that we cannot get down to fundamentals. Dr. Schlesinger started off with definitions of hardness, machinability, and abrasion, but I think he will agree those were not the exact scientific definitions. That is largely the difficulty of this subject, you cannot get down in the first place to positive definitions. The physicist, for example, can define viscosity, the engineer can define tensile strength, but we cannot write down positive definitions of hardness, machinability, and abrasion. If you have a positive definition you know where you are, and can measure consistently that particular property of the material. But we have no exact definitions in regard to these particular properties, although we all have our own ideas of what they mean; we get them, of course, in everyday experience. We have no real measures, so what happens is that we build up by experience and experiment certain arbitrary tests. We have the Brinell test for hardness; it is just an arbitrary test, but one which people have found by experience to be enormously useful. Again, we have, for example, the drill test for machining; again an arbitrary test. And similarly, the various abrasion tests are abitrary tests. Accordingly, it seems to me that as production engineers you have to try out these methods for yourselves. If they work and you find in your own particular job that they are successful, then they are good tests. As I see it, that is the only criterion of

usefulness that one can make in regard to these various tests of hardness, machinability, and abrasion.

Now, in regard to machinability, Dr. Schlesinger has carried out very extensive tests, most valuable tests, and in so doing he has saved the production engineer a terrific amount of work. In my opening remarks I said that I knew little about machinability, but quite frankly, whilst emphasising the value of Dr. Schlesinger's work, I am rather surprised at the conclusion which he has given. In summing up, he said that the Brinell test can be considered under certain circumstances a direct guide to machinability. I say I have had little experience, but I am surprised at that conclusion, and shall be interested to hear the comments of the production people in regard to direct experience in the shops. It seems to me that toughness of a material in addition to hardness must be considered. You can have two materials of exactly similar hardness, but the toughness of the two materials may be quite different. As an example, Hadfield's manganese steel can be given. That material has a Brinell hardness of about 200, but it is extraordinarily tough and most difficult to machine.

Manganese steel is quite definitely one case in which Brinell hardness does not show machinability ; I imagine there are others.

That leads me on to another point in regard to toughness. I agree that generally Brinell hardness is a rough guide to machining properties, but I should like to suggest that the diamond pyramid (Vickers) test might give also some rough indication of toughness. You will remember Dr. Schlesinger showed us the diamond imprints on the screen. Somtimes they are square, sometimes the sides curve outwards, and sometimes they curve inwards. Well, I would rather like to suggest that it might be worth while trying out that if you have two materials of the same Vickers hardens number and on one the impressions curve inwards and on the other curve outwards, the one with inward curves is the more difficult to machine. That might be worth trying out in the machine shop.

With regard to abrasion, I agree quite definitely with Dr. Schlesinger that Brinell hardness and diamond pyramid or Vicker's hardness, do not provide a direct guide to abrasion resistance.

There are one or two further points in regard to abrasion resistance which might be of interest to you and which Dr. Schlesinger has not mentioned. One point is chemical action in relation to abrasion. Probably a number of you have heard of the work of Fink in Germany, on this aspect of abrasion. Using an Amsler Abrasion Machine, Fink ran steel and other test pieces, first of all under normal conditions in the air, and then in an atmosphere excluding all oxygen ; and he found that when he ran the test pieces in air he got oxide forming on the surface as a result of the abrasion, but when he excluded the oxygen then the abrasion and the friction

were very greatly reduced. So that we must remember chemical action in addition to mechanical wear when considering abrasion. Whilst we are on this point, I ought to mention the work that the Institution of Automobile Engineers have been doing in regard to the wear of cylinders, ordinary motor car cylinders, an extremely valuable piece of work of which I am sure automobile engineers in this country will be proud. This work shows fairly conclusively that it is not entirely mechanical abrasion which causes cylinder wear ; there is also corrosion arising probably from the moisture inside the cylinder. Again, in regard to abrasion you have chemical action coming in. Perhaps I can quote one homely example. Those of you who use safety razors ought to know that if you wipe your razor very carefully each morning after you use it and just put a little grease on the edge, then the razor blade will last much longer than it does if you just throw it down wet and allow corrosion to go on. I have tried that out for myself and it certainly does work ; in this case chemical action affects the usefulness of a cutting edge.

DR. SCHLESINGER : I agree with Dr. Hankins that it is difficult to give a scientific definition of Brinell hardness and machinability but the tests were confined, in the special case mentioned, to chromium nickel steel of similar constituents. Manganese steels are rare for use in machines and form another group. There are quite a number of different steel-alloys, and it is, therefore, doubtful that the curve which combines Brinell hardness with machinability is equally valid for all sorts of steels.

The conclusions I gave about that curve were published in 1932, and we should like to hear from the production engineers whether it is right or not. It is so simple that, if proven, it is a very useful guide for the rate fixing department, to select the proper speed for machining.

It should not be forgotten, that to-day the resistance to tensile-stress found by brinelling the piece (" tensile resistance=about $\frac{1}{3}$ Brinell hardness ") is used in most machine-shops by the rate-fixer, to prescribe speeds and feeds ! These rules are just those for which we are looking.

I cannot speak about corrosion, as I am not an expert on that subject.

MR. LOXHAM : There are many things which might be said about the value of Dr. Schlesinger's paper, but I must confine my remarks to a few points. I should like to ask Dr. Schlesinger whether he has found the hydraulic testing apparatus, which he described, to be in every way satisfactory ? I am from a technical college which appreciates the need for giving training to young engineers concerning this new physical property of machinability, and we are, in fact, negotiating for the purchase of an instrument of the type Dr. Schlesinger has described. We have in mind, however, to

purchase an electrical instrument because we think it is superior to the one operating on the hydraulic principle. We should value very highly Dr. Schlesinger's remarks on this point.

The second item to which I should like to refer is the relationship between Brinell hardness and machinability. Production engineers, as a whole, will, I think, appreciate the relationship between the one and the other. I was with a firm of automobile manufacturers about ten years ago, and without going to all the trouble which Dr. Schlesinger has taken, we established a relationship between Brinell hardness and cutting speed. It occurred to someone that there should be a relationship between one and the other, a few tests were carried out in the tool room, and a curve drawn of the type Dr. Schlesinger drew as a result of his researches. This curve was used as the basis for rate fixing.

I can remember instances where even a semi-skilled operator would say "These stampings are hard; I am going to have them brinelled." He would take a stamping to the heat treatment shop and have it tested for hardness. If it was found to be harder than the figure shown on the curve for that particular material, he could demand some form of compensation, or alternatively, the stampings would be re-heat-treated. It is possible to conceive instances where the relationship would not hold, especially on steels susceptible to work hardening. Since, when a chip is being formed during a machining operation, the material fails due to shear, it has occurred to me that there might be even a closer relationship between shear strength and machinability than between hardness and machinability. The value of hardness test as a measure of machinability is considerable, because it does make the testing so much easier.

My last point is that besides making the machine shop try out their own steels for machinability in the way that has been described, surely a paper of this type does give a certain amount of incentive to steel makers to produce steels which have, in addition to the recognised physical properties, a certain standard of machinability. Such an introduction would be a great boon to production engineers. That things are moving in this direction is indicated by the fact that when I visited a large steel works in Sheffield some months ago I saw in use an instrument of the type Dr. Schlesinger has described. This firm claimed that the instrument had largely contributed in the development of a new free cutting steel which they have recently placed on the market. It is their practice to test a sample piece from any billet which must have, in addition to other physical properties, a certain standard of machinability.

DR. SCHLESINGER: The first question was whether the dynamometer ought to be designed hydraulically or electrically. The hydraulic instruments are very simple to handle and to check.

If the hydraulic gauge is stressed with no more than 20 kgs. per square centimeter it works very well. The apparatus is closed in itself and may be set up to another machine in an hour. With an electric dynamometer I had some trouble, but for high forces it seems to be more adaptable. The tool rests on a strong plate of hardened steel which can be changed for different ranges. Therefore, the principle is very good. The trouble is to find good designs for different applications. Last year I used an electric dynamometer universally, but as the leverage from the cutting edge to the supporting surface for such a universal design is generally great, the vibration under heavy strain was as strong as in the case of the hydraulic instrument. The vertical deflection of the supporting diaphragm is decisive. This is about 0.6 mm. for the hydraulic and about 0.2 mm. for the electric instrument using a steel plate.

The next item you mentioned was the proposal to use the shearing stress instead of the tensile stress of Brinell hardness. It is difficult to make shearing tests from ordinary machine parts, having regard to the influence of the shape and the structure of the material to be checked. Take cast iron pieces, and the different resistance lengthwise and crosswise of the steel bars. It is so much easier to make a Brinell test on the piece. If you make turning tests, you can take the Brinell test on the piece itself in some minutes. It is of the greatest importance to have each test under control. We had a Brinell press directly in the second support opposite to the cutting tool set up in the dynamometer.

MR. E. D. BALL: After such a mass of data one is inclined to get a little mental indigestion, but in spite of it all there is one thing which strikes me, and that is that the influence of cutting oils has not been mentioned, or only very incidentally in passing.

There are many varieties of cutting oils but I refer to the general influence on performance. One reference was made to a lathe which was tested in pure air, and the low wear in that case makes one wonder whether if one could keep pure oil between the surfaces, the wear might be reduced to little or nothing.

DR. SCHLESINGER: The influence of cutting oil has been studied very carefully, but not in relation to hardness. If you use a lubricant, you will diminish the heat and will save the tool. Further, lubricants are always diminishing the wear of the tool by abrasion, especially if the cutting fluid is mixed with oil or consists of a pure oil. The more useful quantity of cutting fluid can be measured, which has to be used to find the best result. If you have more than necessary, you will not improve the effect, but if you have less, you diminish the time of endurance of the tool considerably. It is better to overflow the cutting edge with fluid.

You spoke of the use of good oil to diminish wear, with reference to the illustrated abrasion test of the lathe-bed. The air of a

machine shop is generally not pure. There is not only ordinary dust, but also that produced by machining cast iron and other brittle material.

The fine chips fill the air, and if you look at your lathes, you will easily see on the sliding surfaces how the scraped marks are wearing out. The oil runs down from the top, and the tendency is that the solid V-shape is getting dry. You can use a planer for twenty years, because the v's are reversed. There the oil is kept in the opening, and you may even use oil under pressure, so that the v's are overflooded at each stroke. The more carefully you grease, the less is the wear by abrasion. This is a most important point in machine-tool design.

MR. G. H. HALES: Listening to the lecture given by Dr. Schlesinger this evening I am greatly impressed with the volume of data and information he has given us. Our lecturer has provided the Institution of Production Engineers with figures which represent the result of many years of research work, conducted under ideal laboratory conditions, which when put on record will prove a work of reference of high value, which could not be obtained from any better source.

Production engineers will probably use this research information for general guidance, having regard to the fact that there are so many material specifications which vary from those of the materials used in compiling the research data given, and that in actual working practice the machinability of steels and other materials is subject to many variables, such as the condition of the machine tool used, the length and diameter of the piece to be machined, etc., and each set of conditions provides a different problem, affecting machineability.

To give an example, I would refer to vibration as an important factor in the resistance to wear of cutting tools (this also applies to emery wheels). I am sure Dr. Schlesinger would agree that, given a standard test on a lathe, using, say tungsten carbide cutting tools wide variations in results might be expected if cutting tests were taken on certain high tensile steels, of the same material specification but of different diameters and lengths.

If we take the case of machining, say, a motor car rear axle shaft, I have seen tungsten carbide tools stand up for a far greater length of time on this particular component, than was possible on a shorter component of the same material specification. The longer component, in this case, appeared to absorb vibration by flexion in its length against the resistance of the cutting tool—reversing the action of the old goose neck spring tool. Hydraulic feeds, as applied to machine tools in certain cases, also appear to provide conditions favourable as affecting machinability. The examples mentioned would appear to show that the research data given by our lecturer

should be used for general guidance in machinability study, but I consider the variable factors which affect machinability under workshop conditions must always call for local study of each particular problem, with a view to providing such conditions as are conductive to sympathy between cutting tool and material being cut. Used in conjunction with local study of machinability problems the data given by our lecturer may be found most valuable. On behalf of the Institution, I have very great pleasure in proposing a hearty vote of thanks to Dr. Schlesinger for the lecture given this evening. The vote of thanks was cordially adopted.

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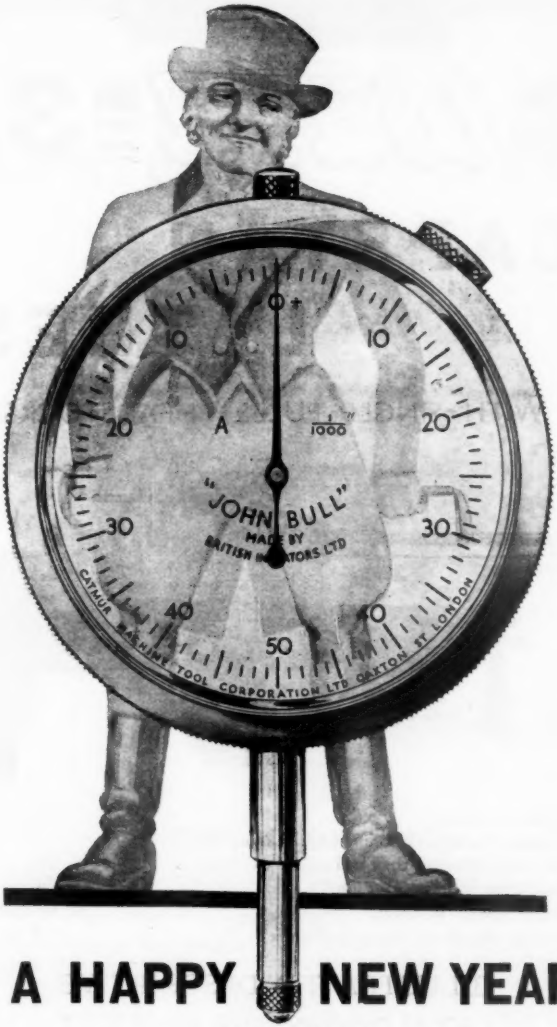

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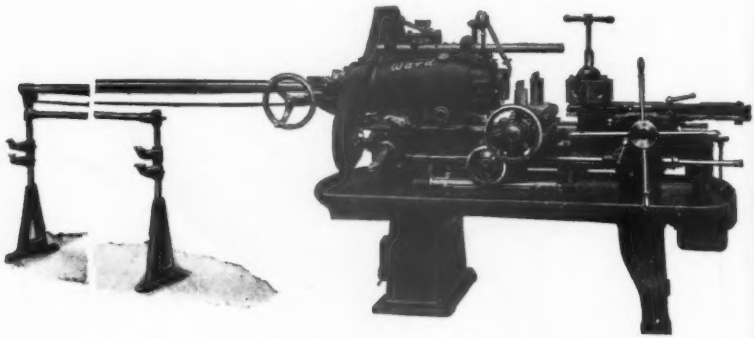

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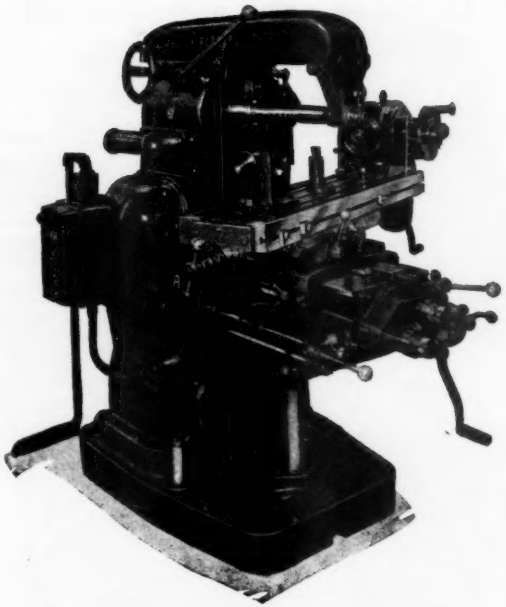

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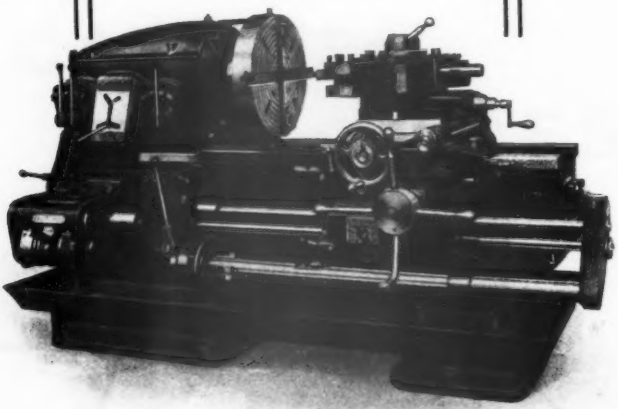

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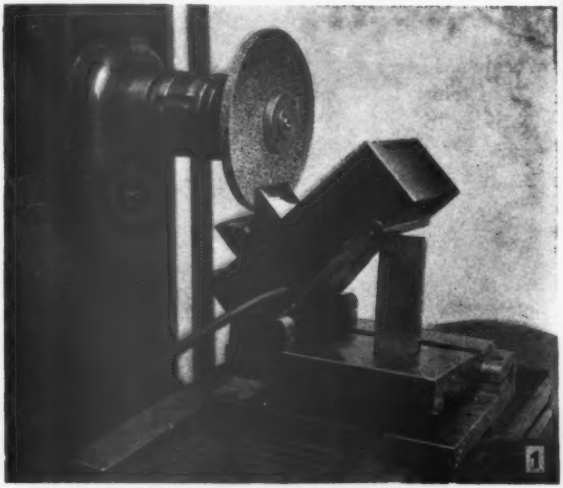

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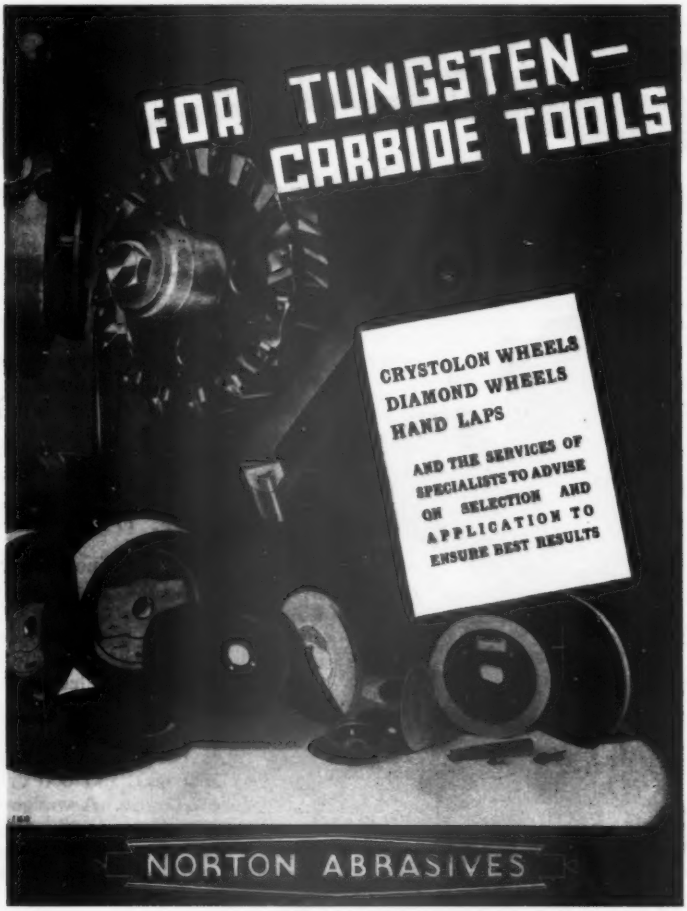

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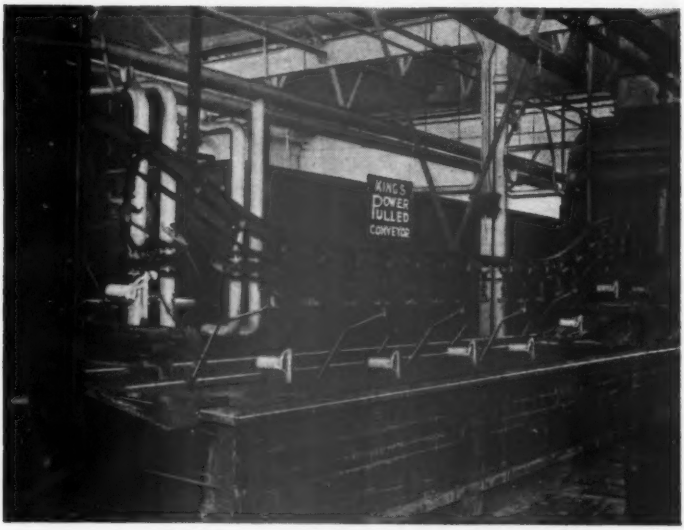

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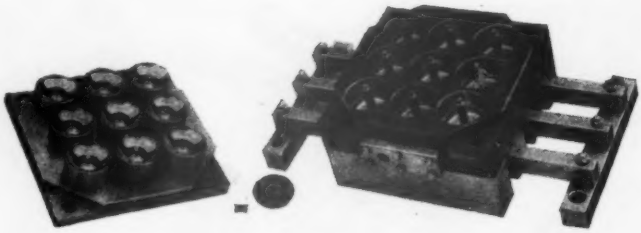

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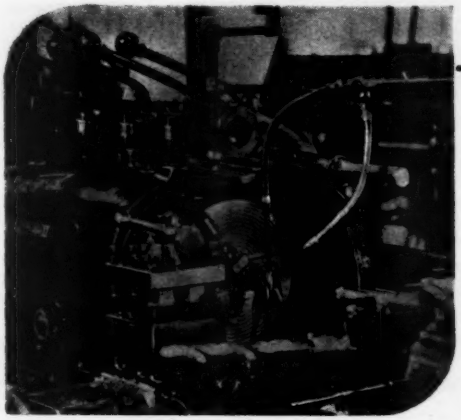

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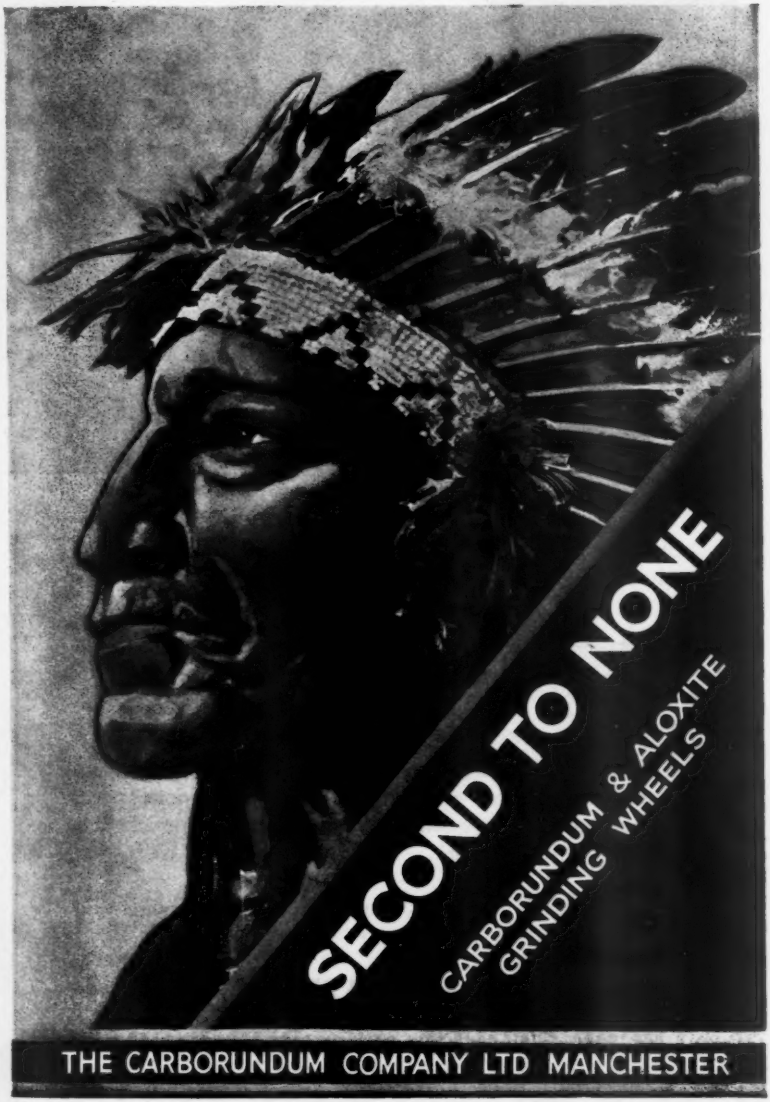
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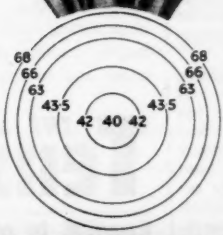

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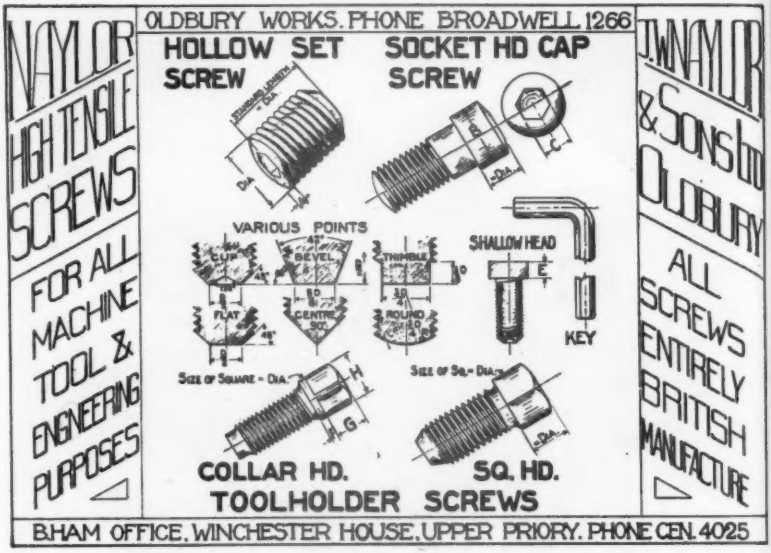

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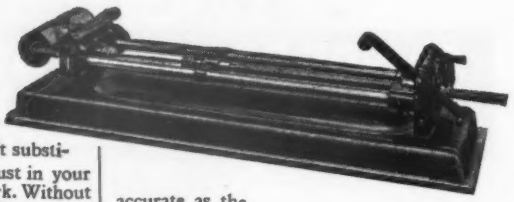

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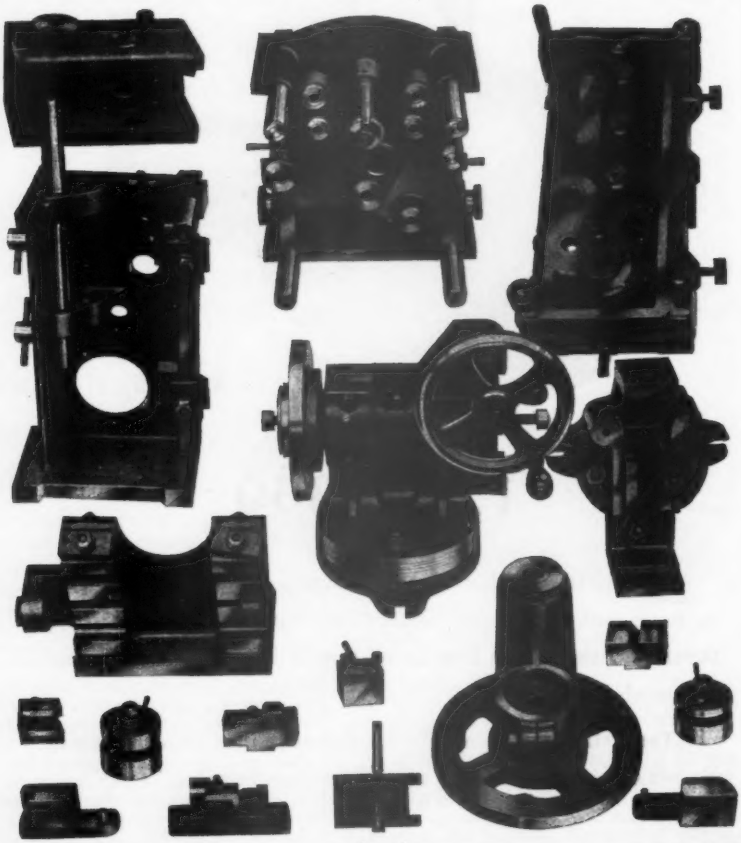

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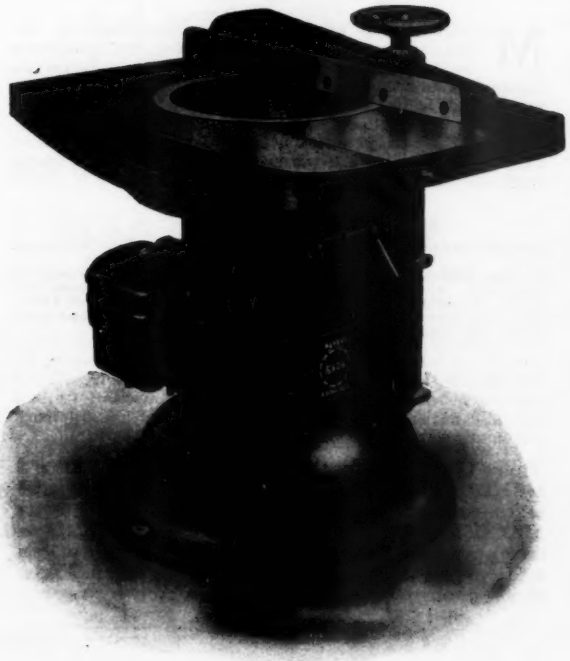

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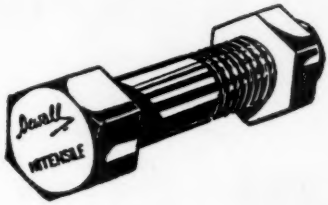

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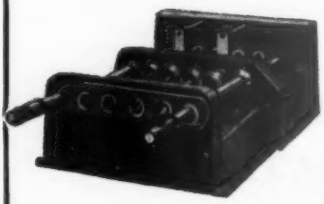

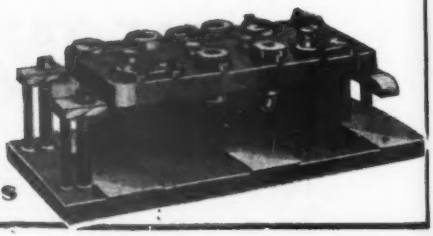

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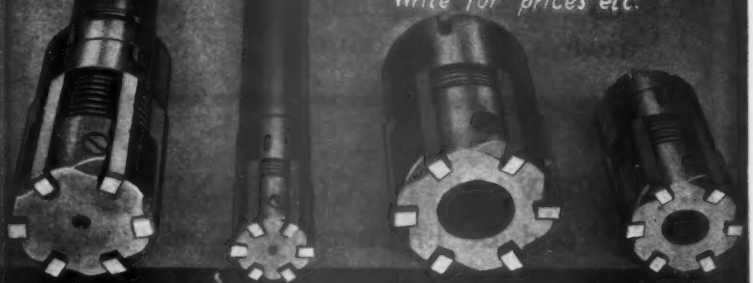

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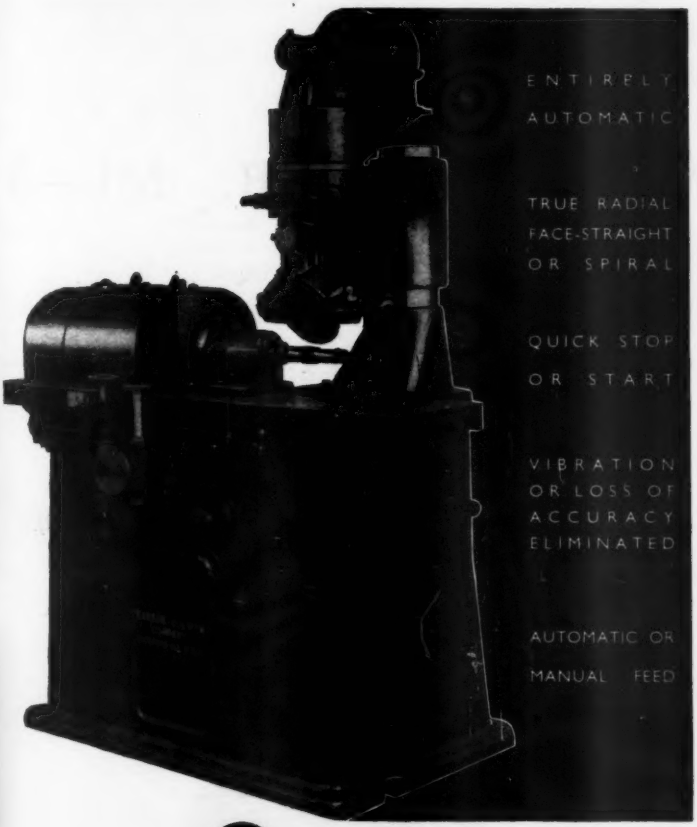

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